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Concretions and nodules in the Hell Creek Formation, southwestern North Dakota

Gerald H. Groenwold

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CONCRETIONS AND NODULES IN THE HELL CREEK FORMATION,
SOUTHWESTERN NORTH DAKOTA

by

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Bachelor of Science, University of Illinois 1967

A Thesis

Submitted to the Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

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This Thesis submitted by Gerald H. Groenewold in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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ABSTRACT

The Hell Creek Formation (Upper Cretaceous) in southwestern North Dakota consists of lagoonal and floodplain deposits and contains abundant concretions and nodules. Representative specimens of the concretions and nodules and their corresponding enclosing sediments were analyzed by thin section and by quantitative and qualitative x-ray diffraction methods.

Fourteen types of concretions and three types of nodules, classified according to shape and composition, have thus been defined. Concretionary types include calcareous sandstone lenses, "logs", and irregular masses; sideritic sandstone lenses and irregular masses; calcareous and sideritic lignitic sandstone lenses; bone-cored rounded masses; coprolite-cored masses; jarosite bodies; pyrite spheres; baritic sandstone lenses; and cone-in-cone masses. The nodular types include siderite masses and lenses and iron oxide spheres. Moving groundwater solutions, in many cases accompanied by locally reducing conditions resulting from the accumulation of organic materials, have apparently been important factors in the formation of many of the concretionary bodies. Precipitation and dewatering of gels is the most probable mechanism responsible for the formation of the various types of nodules.

INTRODUCTION

PURPOSE

Although concretions and nodules are common features in many sedimentary rock units, relatively few detailed studies of these structures have been made. The purpose of this study is to give a detailed description and classification of the concretions and nodules in the Hell Creek Formation of southwestern North Dakota and to propose models for the origin of these structures. In this paper the term "concretion" will be used for structures mineralogically similar to, but generally more resistant than the enclosing sedimentary material and developed by selective deposition of cementing materials from solutions in the pores of a sediment. The term "nodule" will be used for structures consisting of mineral matter unlike and more resistant than the enclosing sedimentary material.

LOCATION

The study area is located in Slope and Bowman Counties of North Dakota. Although the Hell Creek crops out in various other portions of North Dakota and eastern Montana (Frye, 1967), only the Little Missouri valley area in the vicinity of Marmarth was studied (Figure 1). The semi-arid climate and "badlands" topography of this region combine to make it ideally suited for field studies. In addition, there is a greater diversity of types of concretionary and nodular structures than in the other localities.

Figure 1.--Map showing the location of the collecting localities and the outcrop pattern of the Hell Creek Formation. Inset map shows location of the study area.

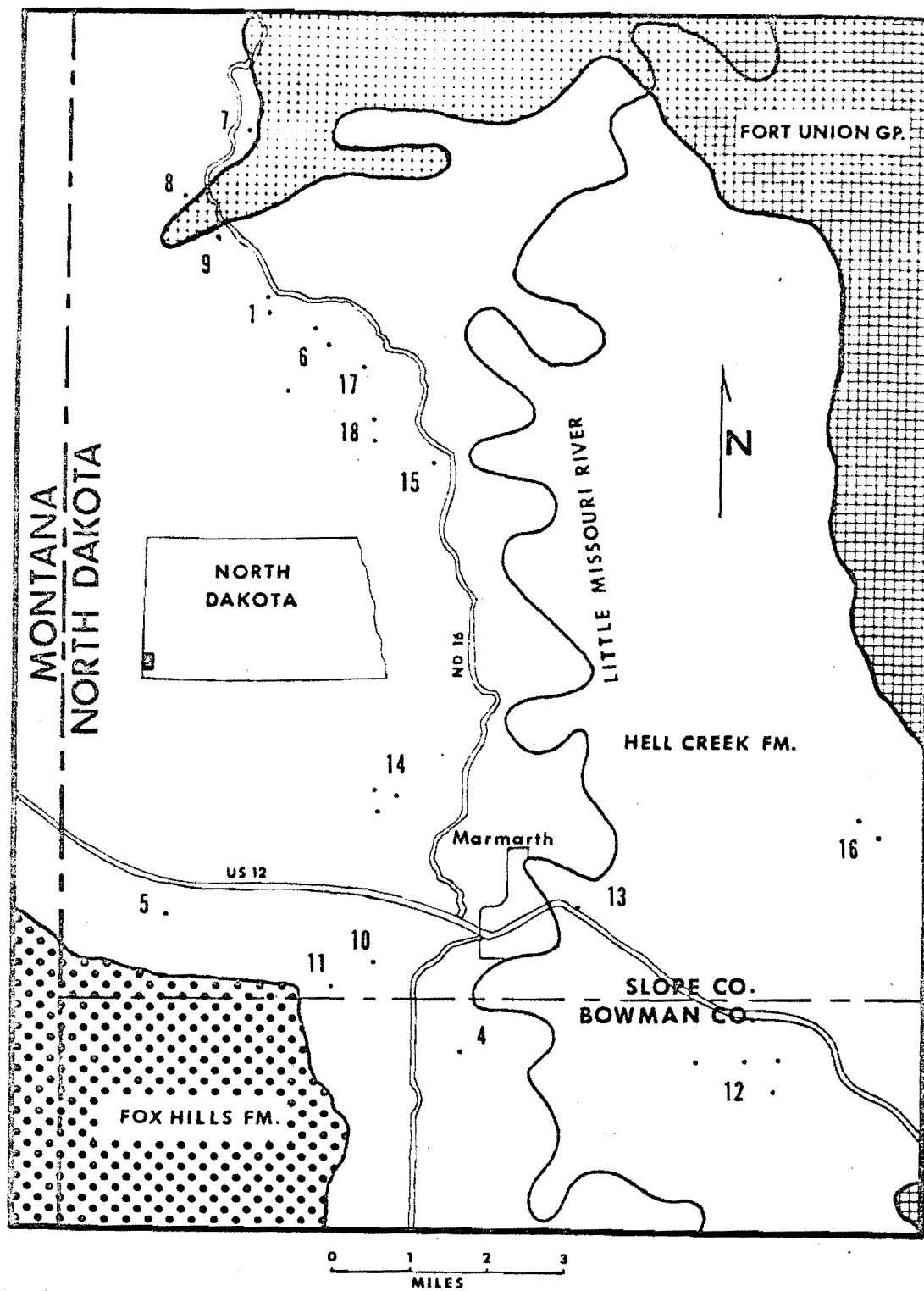


Figure 1.

STRATIGRAPHY OF THE HELL CREEK FORMATION

According to Frye (1969), the Hell Creek Formation is late Cretaceous in age and consists of lagoonal and floodplain deposits. Fine and medium clastic sediments, many of which are lignitic and bentonitic, predominate. The base of the Hell Creek overlies the Fox Hills Formation and is found to become progressively younger to the east. The top of the Hell Creek is the Cretaceous-Tertiary contact and is conformable with the overlying Tertiary sediments.

The Hell Creek is thought to represent the subaerial top-set beds of a large delta which stretched eastward from the Rocky Mountains into the Fox Hills sea. The Fox Hills Formation is visualized as being the marine top-set beds of this delta with the immediately underlying Pierre Shale representing the deltaic fore-set and bottom-set beds (Frye, 1969).

In North Dakota the Hell Creek has been divided into eight members. Five are found in the Missouri Valley and five in the Little Missouri Valley with two of the members, Pretty Butte and Huff, common to both areas. Figure 2 shows the stratigraphic relationships and lithologic descriptions of the Hell Creek and adjacent formations in the study area.

The concretions and nodules collected for this study were generally taken only from the upper four members. Only rarely were concretionary or nodular structures found in the Little Beaver Creek Member.

PREVIOUS WORK

Most early workers concerned with those rock units now included in the Hell Creek Formation gave little more than passing mention to the concretions and nodules. Laird and Mitchell (1942) described some of the types present in the Missouri Valley and gave chemical analyses of certain types. Frye (1967) gave a very good summary of most of the concretions and nodules present in the Hell Creek and included structural,

Age	Fm.	Mbr.	Lithologic Description
TERTIARY	TULLOCK		widespread and continuous lignites, bentonites, sandstones, and bentonitic sediments
CRETACEOUS	HELL CREEK	Pretty Butte	bentonite and bentonitic silts with small sandstone channels; 9 m thick
		Huff	thick sandstone channel deposits with a few, thin, bentonitic shales; 26 m thick
		Bacon Creek	bentonitic sediments, lignitic lenses and occasional sandstone channels; 36 m thick
		Marmarth	two thick sandstone channel deposits separated by thin bentonitic sediments; 23 m thick
		Little Beaver Creek	lignitic sediments and shales as well as some sandstone bodies; 32 m thick
	FOX HILLS		marine sandstones
	PIERRE		marine shales

Figure 2.--Stratigraphic relationships and lithologic descriptions of the Hell Creek and adjacent formations in southwestern North Dakota.

textural, and compositional considerations in his discussion. A preliminary classification based on shape and composition was given by Groenewold and Karner (1969).

FIELD WORK

Field work consisted of collecting representative specimens of all types of concretions and nodules present in the Hell Creek Formation in southwestern North Dakota. No attempt was made to do a statistical analysis of the occurrence of the various structures. Each specimen was located stratigraphically and the location of all collecting sites was recorded on county road maps (Figure 1). Major structural and textural features seen in the field were noted and photographed. Samples of the sediments surrounding each concretion or nodule were also collected for later analysis. A total of 54 specimens and their corresponding sediments were taken. These are housed at the Department of Geology, University of North Dakota.

LABORATORY METHODS

X-ray analysis

Several specimens of each type of concretion and nodule as well as samples of the sediments surrounding each specimen were analyzed using standard x-ray diffraction techniques. Every attempt was made to maintain consistency in preparatory procedures.

Choice of a sample representative of each specimen was often difficult because of the predominance of compositionally zoned structures. The amount of material taken from each of the various zones of the structures was proportional to the total amount of the concretion or nodule represented by that zone.

Initial preparation for x-ray analysis involved hand grinding of

approximately 8 gm of the sample which was split to approximately 2 gm and then ground in a Spex 8000 Mixer Mill for 4 minutes. Each sample was then glycolated for 24 hours at 35° C and 1 gm was then pelletized for x-ray analysis. Avicel-backed pellets were, with minor exception, formed under 7 tons of pressure in a hydraulic press.

The following machine conditions (Karner, 1968) were used for the x-ray analyses:

X-ray Generator (Philips constant potential 50 KV., 50 MA., No. 12215)

X-ray Tube (Machlett Cu tube--short anode 32113) 48 KV., 19 MA.

Diffractometer (Philips high angle 42272/1)
 1° 2θ/minute scan speed,
 1° divergence and anti-scatter slits,
 .006 inch receiving slit,
 Ni filter,
 rotating sample holder.

Detector (Philips scintillation--transistorized 52572) 1.0 KV.

Circuit Panel (Philips 12206/53), Bristol recorder
 PHA, width 9 V., level 7 V.,
 linear scale,
 1 second time constant,
 2 X 10⁵ counts/second (or greater) full scale,
 30 inches/hour chart speed.

Weight percentages of minerals present in the samples were determined according to the method developed by Alexander and Klug (1948).

This method utilizes the following relationship:

$$X_1 = \frac{I_1 \mu_s^*}{(I_1)^0 \mu_1^*}$$

where X_1 = weight fraction of component 1
 μ_1^* = mass absorption coefficient of component 1
 μ_s^* = mass absorption coefficient of powder sample
 I_1 = intensity diffracted at a definite Bragg angle 2θ by a crystalline component 1
 $(I_1)^0$ = intensity diffracted at a definite Bragg angle 2θ by pure crystalline component 1

X-ray diffractometer charts of the samples were overlaid on a master

chart which had been corrected to an estimated mass absorption coefficient of 60. Mineral percentages were then determined directly from peak heights and were corrected to the nearest part per ten. Amounts less than 5 percent were designated as M. The compositional variability within any distinct group of concretions or nodules makes any attempt at greater accuracy meaningless.

Thin section analysis

Thin sections of 46 specimens of concretions and nodules were studied. Textural, structural, and mineralogical characteristics of each were noted. Photomicrographs were made of certain outstanding features.

RESULTS OF INVESTIGATION

CLASSIFICATION

The concretions and nodules in the Hell Creek Formation show a great deal of compositional and textural variation. Such variations are evident in both field and laboratory investigations and have been used to classify these structures. Table 1 shows the classification as developed by Groenewold and Karner (1969) and modified by the present author. Mineralogical composition as determined from x-ray analysis as well as other important characteristics of individual concretion and nodule types are included in the same table. Compositions are given for a specimen which had a composition approximately equal to the average for all specimens examined in that group.

DESCRIPTIONS OF CONCRETIONS

Calcareous sandstone lenses

Calcareous sandstone lenses are abundant in the Hell Creek Formation. These structures are most commonly found in the channel-sand units of the Marmarth and Huff Members. Lenses of this type show very large variations in size, ranging from 1-10 m in length and 0.1-2 m in thickness. They are always elongated parallel to bedding. They are seldom restricted to particular bedding planes, but rather, are scattered throughout the associated sand units (Figure 3a). Commonly the lenses are more resistant than surrounding sediments and typically preserve undisturbed primary sedimentary structures such as bedding (Figure 3b). Relationships to cross-bedding indicate that the orientation

TABLE 1

CLASSIFICATION AND CHARACTERISTICS
OF CONCRETIONS, NODULES, AND CORRESPONDING SEDIMENTS
OF THE HELL CREEK FORMATION, SOUTHWESTERN NORTH DAKOTA

Type	*Composition of Typical Specimen													
	illite	montmorillonite	mica	chlorite	kaolinite	quartz	K-feldspar	plagioclase	calcite	dolomite	siderite	Fe oxide	apatite	Jarosite
Concretions													pyrite	barite
1. Calcareous ss lens Sediment	m 1	m -	- -	2 1	1 1	5 -	- -	- -	- -	- -	- -	- -	- -	- -
2. Calcareous ss irregular mass (1) Sediment	1 2	m m	m m	2 2	3 -	- -	- -	- -	- -	- -	- -	- -	- -	- m
3. Calcareous ss irregular mass (2) Sediment	1 2	m m	m m	4 1	2 -	- -	- -	- -	- -	- -	- -	- -	- -	- -
4. Calcareous ss "log" Sediment	m m	- -	- -	1 m	m 9	- -	- -	- -	- -	- -	- -	- -	- -	- -
5. Sideritic ss lens Sediment	1 3	- -	- -	4 1	1 -	- -	- -	- -	- -	- -	- -	- -	- -	- -
6. Sideritic ss irregular mass Sediment	m m	m -	- -	2 m	1 6	- -	- -	- -	- -	- -	- -	- -	- -	- -
7. Lignitic calcareous ss lens Sediment	1 1	m m	m m	4 1	2 -	- -	- -	- -	- -	- -	- -	- -	- -	- -
8. Lignitic sideritic ss lens Sediment	- -	m -	- -	2 1	1 -	- -	6 m	- -	- -	- -	- -	- -	- -	- -
9. Bone-cored rounded mass Sediment	1 2	m m	m m	2 2	2 -	1 -	- -	- -	- -	- -	- -	- -	- -	- m
10. Coprolite-cored mass Sediment	2 3	m m	m m	3 1	1 -	m -	- -	- -	- -	- -	- -	- -	- -	- -
11. Jarosite body Sediment	m m	- -	- -	1 1	1 5	- -	- -	- -	- -	- -	- -	- -	- -	- 1
12. Pyrite sphere Sediment	2 2	m m	m m	3 1	2 -	m -	- -	- -	- -	- -	- -	- -	- -	- -
13. Baritic ss lens Sediment	- -	- -	- -	1 -	m 3	- 2	3 -	- -	- -	- -	- -	- -	- -	- 1
14. Cone-in-cone mass Sediment	1 2	m m	m m	4 1	2 -	m -	- -	- -	- -	- -	- -	- -	- -	- -
15. Siderite mass Sediment	m -	- -	- -	1 m	m 1	- -	t 8	- -	- -	- -	- -	- -	- -	- m
16. Siderite lens Sediment	3 1	m m	m m	4 1	1 -	- -	- -	- -	- -	- -	- -	- -	- -	- -
17. Iron oxide spheres Sediment	- -	- -	- -	1 -	m m	- -	- -	- -	- -	- -	- -	- -	- -	- -
18. Pyrite sphere Sediment	1 2	m m	m m	4 1	1 -	- -	- -	- -	- -	- -	- -	- -	- -	- -
19. Baritic ss lens Sediment	- 2	m m	- -	4 1	2 -	- -	t -	1 -	- -	- -	- -	- -	- -	- t
20. Pyrite sphere Sediment	1 2	m m	- -	4 1	2 -	m -	- -	- -	- -	- -	- -	- -	- -	- -
21. Baritic ss lens Sediment	m -	- -	- -	2 1	1 -	- -	- -	- -	- -	- -	- -	- -	- -	- -
22. Cone-in-cone mass Sediment	3 m	m m	m m	4 1	1 -	1 -	- -	- -	- -	- -	- -	- -	- -	- -
23. Baritic ss lens Sediment	m -	- -	- -	2 1	1 -	- -	- -	- -	- -	- -	- -	- -	- -	- -
24. Cone-in-cone mass Sediment	1 3	m m	- -	5 m	1 -	- -	- -	- -	- -	- -	- -	- -	- -	- m
25. Cone-in-cone mass Sediment	- -	- m	- -	2 1	1 6	- -	- -	- -	- -	- -	- -	- -	- -	- m
26. Cone-in-cone mass Sediment	2 2	m m	m m	4 1	1 -	- -	- -	- -	- -	- -	- -	- -	- -	- -
Nodules														
15. Siderite mass Sediment	m -	- -	- -	1 -	- -	- -	8 1	- -	- -	- -	- -	- -	- -	- -
16. Siderite lens Sediment	1 2	m m	m m	4 m	1 -	- -	- -	- -	- -	- -	- -	- -	- -	- -
17. Iron oxide spheres Sediment	t -	- -	- -	m -	- -	- -	9 m	- -	- -	- -	- -	- -	- -	- -
18. Pyrite sphere Sediment	1 3	m -	m 6	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
19. Baritic ss lens Sediment	- -	m -	- -	1 -	- -	- -	1 8	- -	- -	- -	- -	- -	- -	- -
20. Pyrite sphere Sediment	1 2	m m	- 3	1 1	- 1	- -	- -	- -	- -	- -	- -	- -	- -	- -

*Composition of typical specimen in parts per ten (m = minor, t = trace).

TABLE 1--Continued

Type	Relative Abundance	Size Range	Relation to Bedding
1.	abundant	1-10 m in length, 0.1-2 m thick	random distribution
2.	abundant	0.5-1 m in diameter	concentrated in layers
3.	rare	0.5-1 m in diameter	concentrated in layers
4.	common	5-15 m in length, 1-3 m in diameter	random distribution
5.	common	1-3 m in length, 0.2-1 m in diameter	random distribution
6.	common	0.5-1 m in diameter	concentrated in layers
7.	rare	1-5 m in length, 0.5-1 m thick	random distribution
8.	abundant	5-20 m in length, 0.5-2 m thick	concentrated in layers
9.	common	5-20 cm in diameter	random distribution
10.	rare	5-10 cm in diameter	random distribution
11.	common	10-30 cm in diameter	random distribution
12.	rare	2-5 cm in diameter	random distribution
13.	rare	0.5- 1 m in length, 5-10 cm thick	random distribution
14.	rare	0.5-2 m in diameter	random distribution
15.	abundant	0.1-0.2 m in diameter	concentrated in layers
16.	rare	1-2 m in length, 2-10 cm thick	concentrated in layers
17.	rare	0.1-0.5 m in diameter	concentrated in layers

Figure 3a.--Calcareous sandstone lenses in the Marmarth Member,
sec. 25, T. 133 N., R. 106 W., Slope County, North Dakota.

Figure 3b.--Calcareous sandstone lens enclosing undisturbed
bedding in sandstone of the Marmarth Member at locality 5,
sec. 26, T. 133 N., R. 106 W., Slope County, North Dakota.



Figure 3a.



Figure 3b.

of the longest axes of the lenses are parallel to the paleodrainage (Frye, 1967). Gradation of calcareous sandstone lenses to sideritic sandstone lenses is common with all possible intermediate types represented. Compaction of the sediments around the calcareous lenses is lacking and the sediment-concretion contact is commonly gradational.

Thin sections show calcite cement throughout the concretion with little evidence of disturbance of floating clastic grains due to calcite growth (Figure 4a). A few scattered lignitic fragments are present with no apparent relation to cementing activities. Fracturing and splitting of clastic grains (plagioclase usually) is present but relatively rare (Frye, 1967). Most clastic grains are rimmed by short elongated calcite crystals which are oriented perpendicular to the surface of the grains. Often fibrous calcite is present on only one side of a clastic grain (Figure 4b). Many grains are partially replaced by calcite. Most of the calcite is fine-grained and massive although plumose types are sometimes seen. Small limonitized siderite crystals are scattered throughout the lenses. Frye (1967) has also noted the presence of plumose calcite perpendicular to bedding and concluded that this indicated minor expansive growth between laminae. This was not seen by the present writer.

Calcareous sandstone irregular masses

Two types of these concretions were found. One type is relatively abundant and is found in the sandy sediments of the Marmarth, Bacon Creek, and Huff Members as lumpy, globular masses which are restricted to a definite stratigraphic zone. They range in size from 0.5-1 m in diameter. Bedding usually continues undisturbed through the masses, the only exceptions were a few specimens which had been transected by a series of branching calcite veins. Such veins cut across primary, as well as the latter concretionary, structures. Occasionally, such

Figure 4a.--Thin section in plane-polarized light of a calcareous sandstone lens showing shattering of plagioclase grains (light) by calcite cement (dark) from the Marmarth Member at locality 5 (90X) (UND Catalog No. 6291).

Figure 4b.--Thin section in plane-polarized light of a calcareous sandstone lens showing fibrous calcite on only one side of many of the clastic grains from the Marmarth Member at locality 5 (90X) (UND Catalog No. 6291).

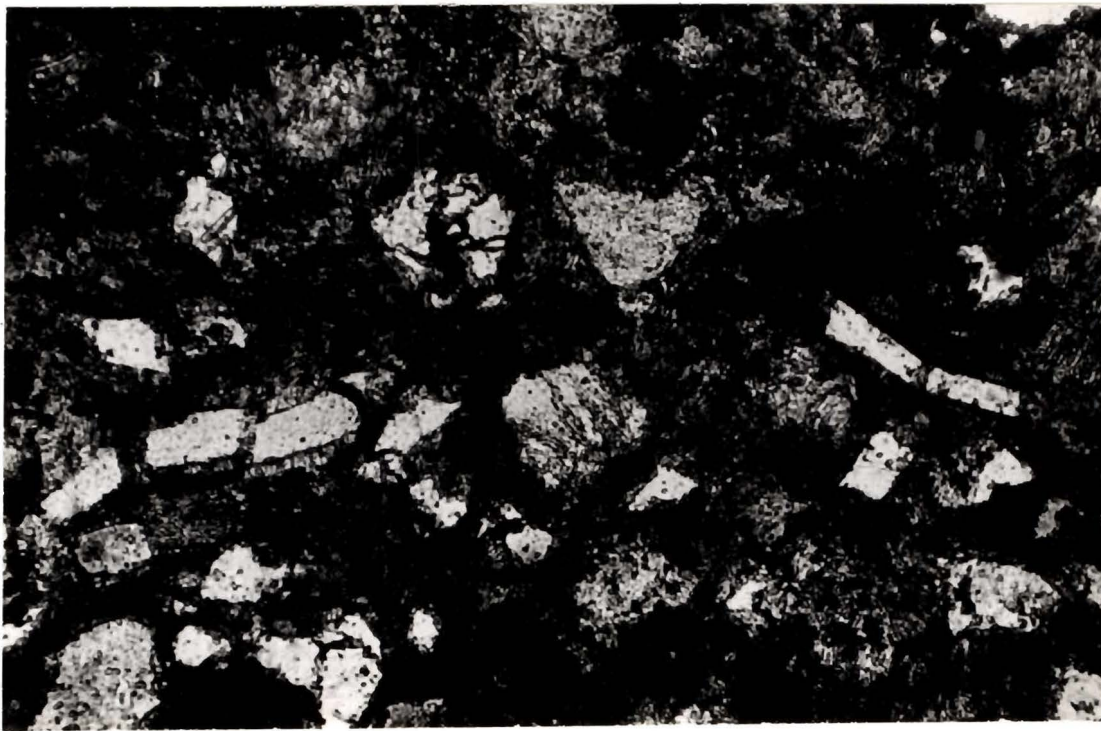


Figure 4a.

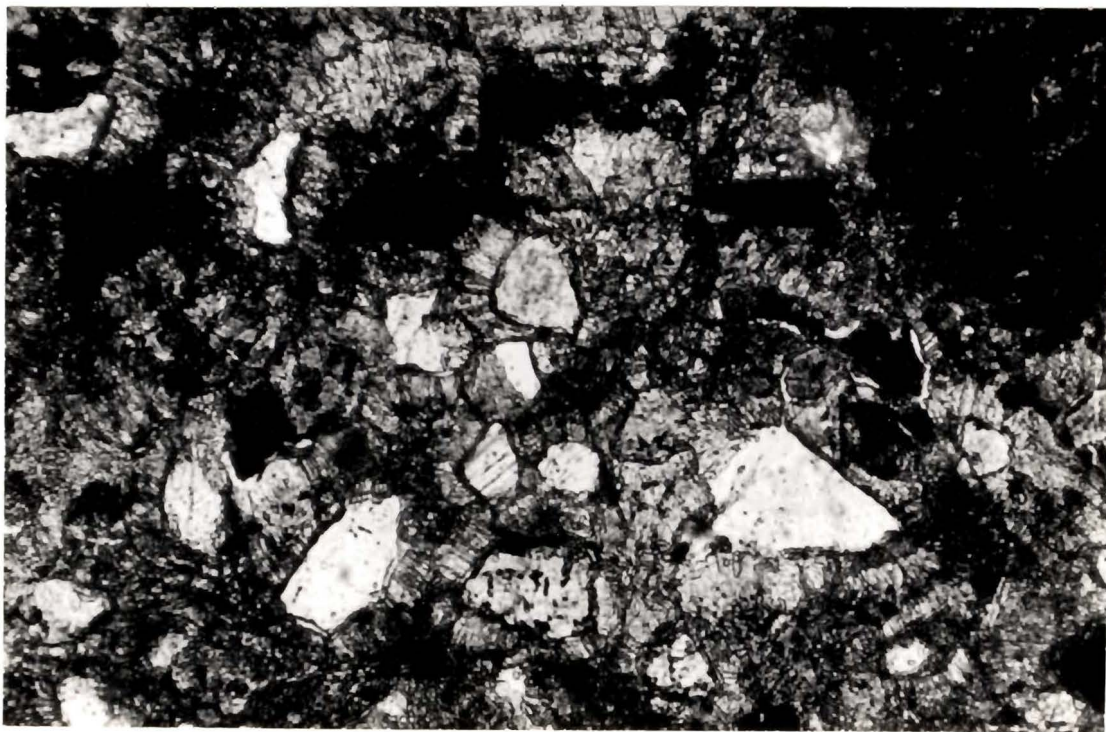


Figure 4b.

concretions grade into sideritic sandstone bodies of a similar shape. Differential compaction of the surrounding sediment is common.

Figure 5a illustrates a typical specimen. Lignitic material as well as a few siderite rhombs, weathered to limonite and accompanied by areas of limonitic staining are present. Splitting of some of the floating clastic grains can also be seen. The cement is predominantly very fine-grained calcite which is commonly massive, but occasionally plumose to fibrous. Figure 5b shows a thin section of a typical specimen which is transected by branching calcite veins. The veins consist of sparry calcite crystals aligned perpendicular to the edges of the branches. The concretion has an "exploded" appearance in that the veins are separating areas which were obviously joined prior to growth of the sparry calcite. These separated areas contain massive calcite cement and much lignitic material. Limonitic staining is very evident and calcite replacement of clastic grains is present around grain margins. In addition, fibrous calcite, where present, is often found on only one side of the grain.

The other type defined within this group is very rare and was found at only one location. These concretions are highly calcareous (Table 1) and were found in an extremely bentonitic unit in the Bacon Creek Member. They are very striking in the field because of the contrast between the light cream-colored concretion and the dark gray, enclosing sediments (Figure 6). The shape of such concretions is variable but usually approximates an ellipsoid. The size of the largest dimension varies from 0.5-1 m. Bedding continues through the concretion with no noticeable disturbance. In addition, the concretions are relatively restricted to a particular zone within the enclosing sediments. They are striking in thin section, being nearly 90 percent granular calcite with minor amounts of clay and highly altered clastic grains (Frye, 1967).

Figure 5a.--Thin section in plane-polarized light of the first type of calcareous sandstone irregular mass showing splitting of clastics (light) by calcite (dark) from the Marmarth Member at locality 10 (90X) (UND Catalog No. 6302).

Figure 5b.--Thin section in plane-polarized light of a calcareous sandstone irregular mass showing calcite veins from the Marmarth Member at locality 11 (2.5X) (UND Catalog No. 6303).

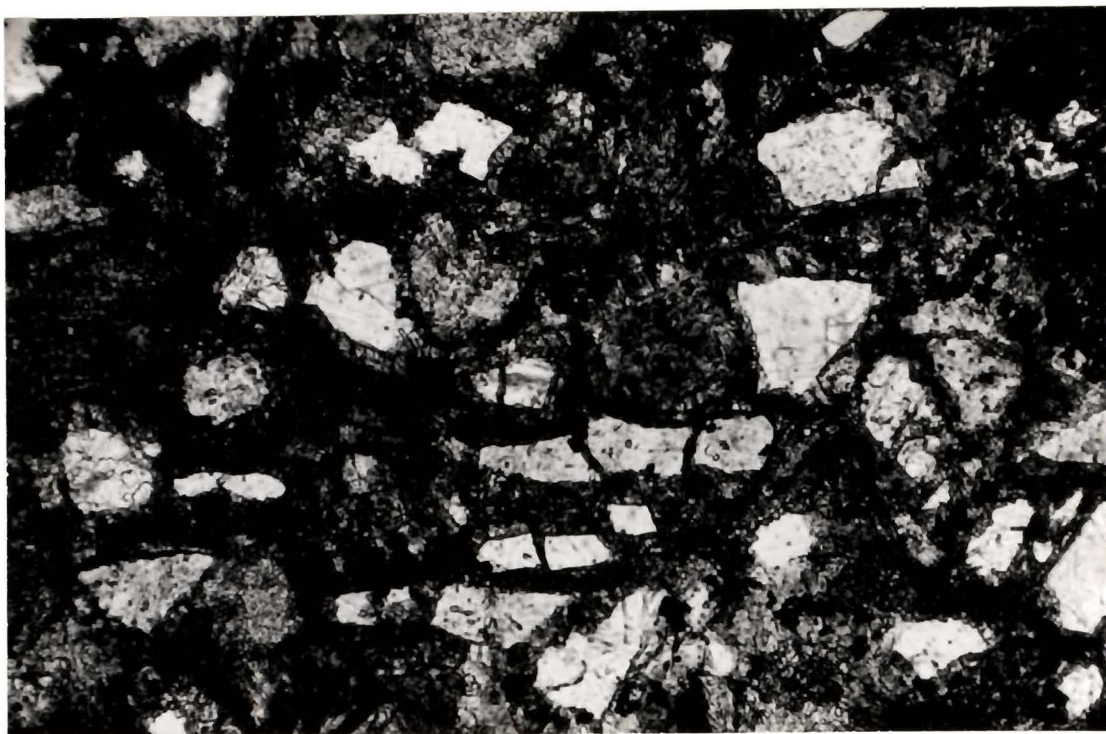


Figure 5a.



Figure 5b.

Figure 6.--Second type of calcareous sandstone irregular mass
in the Bacon Creek Member at locality 16, sec. 25, T. 133 N.,
R. 105 W., Slope County, North Dakota.



Figure 6.

Calcareous sandstone "logs"

"Log" concretions are common in the channel sands of the Huff Member of the Hell Creek Formation. Shape and size distinguish "log" concretions from calcareous sandstone lenses. The "logs" are ellipsoidal in cross section as opposed to a more tabular shape for the lenses. As in lenses, the long axis is oriented parallel to the bedding. The "log" concretions are always large, ranging from 10-15 m in length as opposed to 1-10 m for lenses. Figure 7a shows a typical example of a "log" concretion. The "logs" are always parallel to one another in a given outcrop and included cross-bedding indicates parallelism to paleodrainage (Frye, 1967).

The thin section study of a typical "log" concretion indicated little variation from the calcareous sandstone lenses. The only difference between the two concretionary types is in the amount of limonitic material present; the lens having a considerable amount of such staining whereas the "log" has very minor amounts. The two concretionary types are essentially identical in all other characteristics.

Sideritic sandstone lenses

Sandstone lenses cemented with siderite are rare in the Hell Creek Formation. They are found in a few localities within sand units in the Marmarth and Bacon Creek Members. They are gradational with calcareous sandstone lenses. Figure 7b shows a typical example which grades into a calcareous sandstone lens. Sideritic sandstone lenses are similar in shape and size to calcareous sandstone lenses although variation in size within each group is very large (Table 1). Similarly, little disturbance of the enclosed bedding is to be found in the sideritic sandstone lenses and random distribution within the enclosing sediment with the long axis oriented approximately parallel to the bedding is

Figure 7a.--"Log" concretion in the Huff Member at locality 18,
sec. 23, T. 134 N., R. 106 W., Slope County, North Dakota.

Figure 7b.--Sideritic sandstone lens (diagonal) grading into a
calcareous sandstone lens (upper right) in the Marmarth
Member at locality 4, sec. 9, T. 132 N., R. 106 W., Bowman
County, North Dakota.

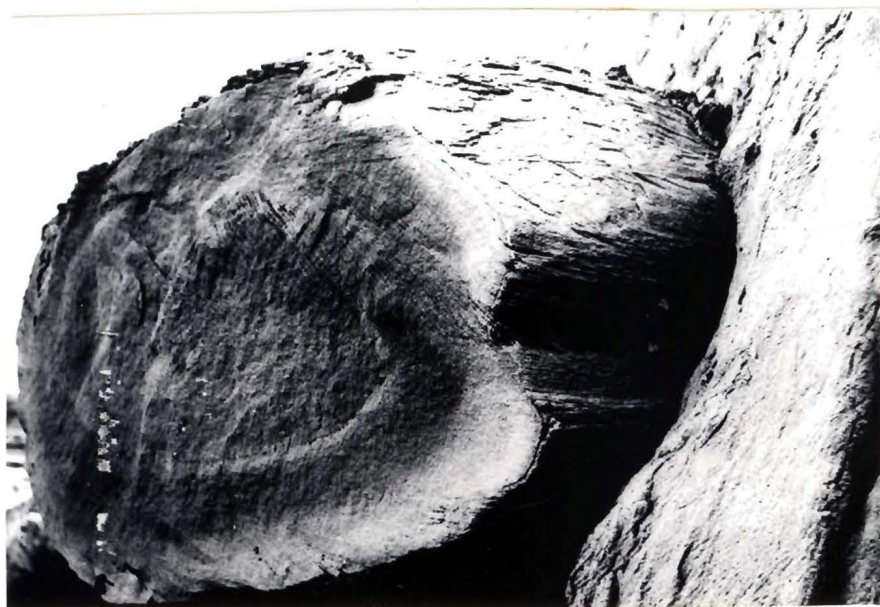


Figure 7a.



Figure 7b.

characteristic. The concretion-sediment contact is typically gradational.

Thin sections show minor sideritic replacement of floating clastic grains with occasional fracturing of the clastic grains. The siderite is massive and fine-grained and very slightly to almost completely altered to limonite. Organic material is usually present in minor amounts. Except for the difference in cementing material, thin sections of sideritic sandstone lenses are identical to those of calcareous sandstone lenses.

Sideritic sandstone irregular masses

Concretions of this type are common in the Hell Creek Formation and can be found in all but the Little Beaver Creek Member. This concretionary type is often gradational with calcareous sandstone irregular masses and of a similar form and size. They are concentrated along certain bedding planes with included primary structures apparently undisturbed; however, minor compaction of the sediments around the concretions has occurred. In the field they appear as reddish-brown globular masses which protrude from the surrounding sediments (Figure 8).

Thin sections show minor to almost complete alteration of the siderite to limonite. Organic material is common as is sideritic replacement of the floating clastic grains. The siderite-limonite is cryptocrystalline and massive with no noticeable fracturing of the clastic grains present.

Lignitic calcareous sandstone lenses

Calcareous sandstone lenses containing greater than 10 percent organic matter are rare in the Hell Creek Formation but do occur in the Huff and Bacon Creek Members. Such lenses are randomly distributed relative to bedding with the long axes oriented parallel to the bedding. They range in size from 1-5 m in length and 0.5-1 m in thickness. The outer surfaces were often slickensided during compaction of the enclosing

Figure 8.--Sideritic sandstone irregular masses in the Bacon
Creek Member at locality 12, sec. 23, T. 133 N., R. 105 W.,
Slope County, North Dakota.



Figure 8.

sediment. In general, they are found in sandy sediments which contain lignitic materials, although usually not as much as is found in the concretions themselves. Figure 9a shows a typical example.

Thin sections show the calcite cement to be composed of large fibrous crystals interspersed with lesser amounts of fine, massive calcite. In many instances, the fibrous calcite is concentrated on only one side of a clastic grain and is consistently found on the same side of the grains. In addition, calcite replacement of the floating clastic particles is common and minor fracturing of some of the grains is noticeable. Limonitic staining is present throughout the concretions.

Lignitic sideritic sandstone lenses

Concretions of this type are abundant and include all the sideritic sandstone lenses which contain greater than 10 percent organic matter. These lenses are generally larger than the sideritic sandstone lenses, ranging from 5-20 m in length and 0.5-2 m in thickness, and are found only in the lignitic, bentonitic sediments of the Bacon Creek, Huff, and Pretty Butte Members. Figure 9b shows a typical hand specimen. Concretions of this type are concentrated in layers with their longest axes approximately parallel to bedding. There is usually some disturbance of enclosed primary structures and the outer surfaces are invariably altered to limonite.

Some lenses demonstrate at least two stages of development with the earlier-formed feature disrupted by later episodes of cementation and growth. Figure 10 shows a very good example of such a "multiple-stage" concretion. It is apparent that this specimen was originally a lignitic sideritic sandstone lens. Later growth of plumose, fibrous, and granular calcite has resulted in a shattering of the sideritic material, and in some places, a complete replacement of the original concretionary

Figure 9a.--Lignitic calcareous sandstone lens showing slicken-sides in the Huff Member at locality 1, sec. 16, T. 134 N., R. 106 W., Slope County, North Dakota.

Figure 9b.--Specimen of a lignitic sideritic sandstone lens containing fossilized wood from the Bacon Creek Member at locality 14 (UND Catalog No. 6311).



Figure 9a.

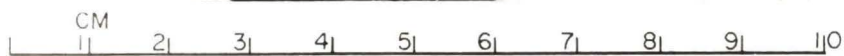


Figure 9b.

Figure 10.--Thin section in plane-polarized light of a lignitic sideritic sandstone lens showing shattered effect due to later growth of calcite from the Huff Member at locality 1 (90X) (UND Catalog No. 6282).

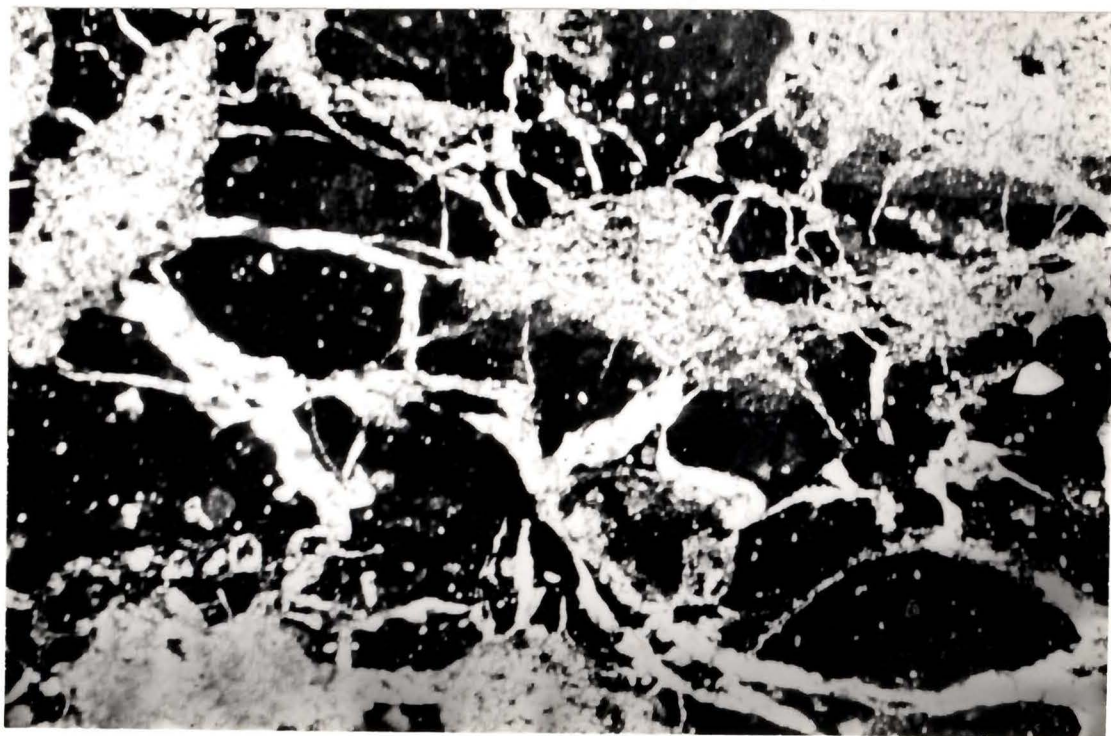


Figure 10.

materials. This shattering effect is evidenced by numerous cross-cutting relationships of the calcite relative to the siderite and some clastic grains. Carbonate replacement (both calcite and siderite) of the floating clastics is evident throughout the thin section as is limonitic staining which has resulted from the alteration of the siderite and other iron-rich minerals.

Bone-cored rounded masses

Bone-cored concretions (Figure 11) are found in lignitic, bentonitic, fine-grained sediments. Although found only in the Bacon Creek Member, concretions of this type are relatively common features concentrated in thick limonite-stained zones. A typical specimen is egg-shaped; however, this type of concretion will often take a shape similar to that of the included bone, thereby allowing for a multitude of possible forms. They are typically small, ranging in size from 5-20 cm in the largest dimension. The included bone usually consists of a fragment of a much larger bone and is invariably completely apatized. The rind which surrounds the bone consists of about equal parts detrital grains (mostly quartz) and calcite and is of a variable thickness. In addition, there is minor organic material and limonite, which gives the rind its reddish-brown color. Concretions of this type are found randomly distributed relative to any given bedding surface; however, they are restricted to definite lignitic zones which vary from 0.5-2 m in thickness. There is no compaction of the sediments around the concretions and the sediment-concretion contact is gradational.

Thin sections of typical specimens indicate that the rind consists of partially altered clastic grains, mostly of quartz and feldspar, floating in a limonite-stained cryptocrystalline calcite matrix. Fracturing of some of the clastic grains is evident.

Figure 11.--Bone-cored rounded mass sectioned through the middle showing bone fragment and rind from the Bacon Creek Member at locality 14 (UND Catalog No. 6313).

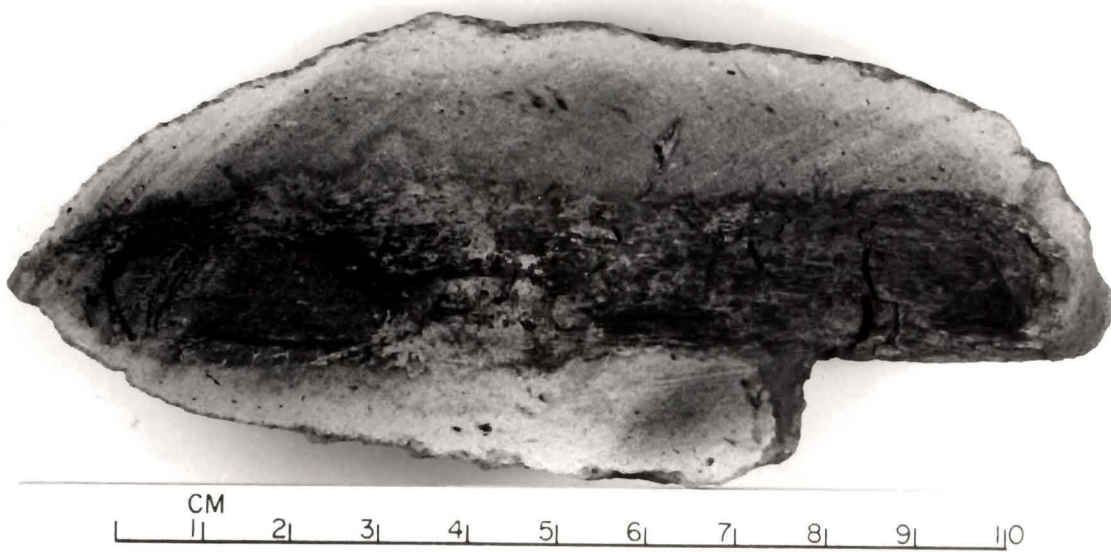


Figure 11.

Coprolite-cored masses

Concretionary bodies which have formed about a coprolite are rare in the Hell Creek Formation and are found only in the sandy bentonite units of the Pretty Butte Member (Frye, 1967). A typical specimen (Figure 12a) is egg-shaped and consists of a light tan to cream-colored outer rind surrounding a mottled gray to black, apatized, coprolitic core. They are very small, from 5-10 cm in diameter. Concretions of this type are randomly scattered relative to bedding. Compaction of the enclosing sediments, if present, cannot be distinguished because of their fine-grained texture.

Upon first examination there does not appear to be any disturbance of bedding by the concretionary growth. However, thin sections show that minor disturbances have occurred. As shown in Figure 12b, micro-faults have disrupted the outer rind, thus implying some sort of disturbance during formation of the concretion. The calcite in the outer rind is cryptocrystalline and without noticeable structure. Minor replacement of the floating detrital quartz is a common feature; however, fracturing of the quartz by calcite is not evident.

Jarosite bodies

Jarosite concretions (Figure 13) are common in the sand units of the Bacon Creek, Huff, and Pretty Butte Members of the Hell Creek Formation. Such concretions are usually found as spheres; however, irregular nodular types as well as flattened forms are also present in some localities. They range in size from 19-30 cm in diameter. All are very poorly consolidated and only their yellow color distinguishes them from the surrounding sediments. Zoning is very common in the form of alternating yellow and brown zones of jarosite and limonite. Invariably these alternating zones surround one or more nuclei which

Figure 12a.--Sectioned coprolite-cored mass showing typical core and rind from the Pretty Butte Member at locality 6 (UND Catalog No. 6293).

Figure 12b.--Thin section in plane-polarized light of a coprolite-cored mass showing micro-faulting in the rind from the Pretty Butte Member at locality 6 (2.5X) (UND Catalog No. 6293).

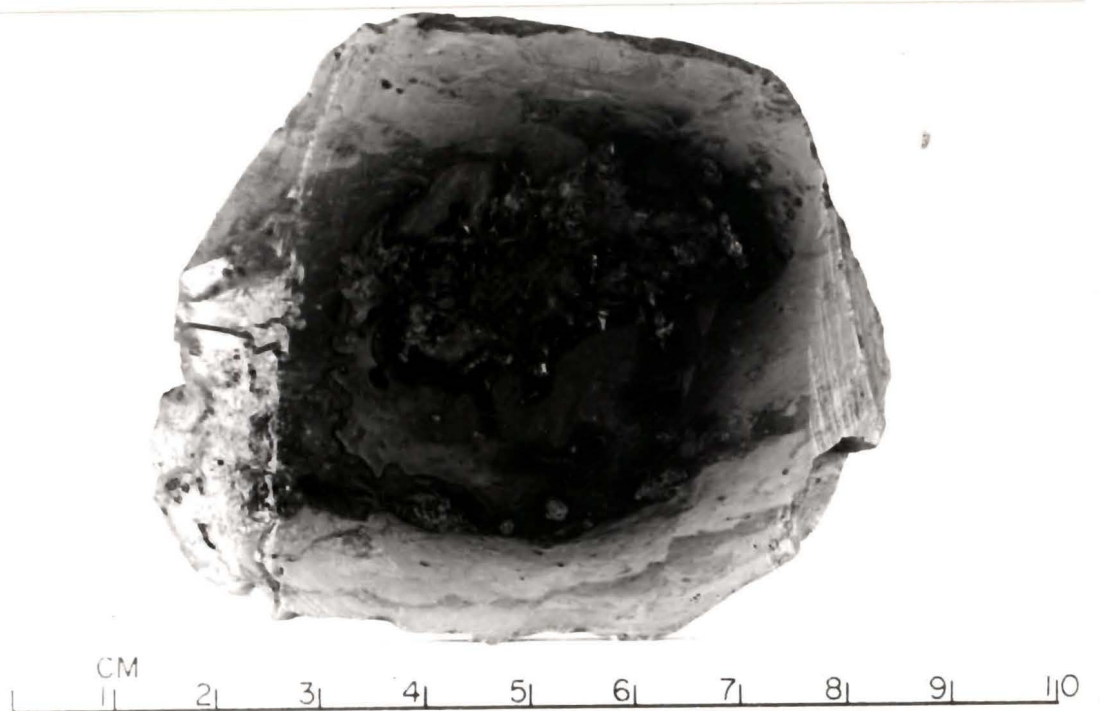


Figure 12a.

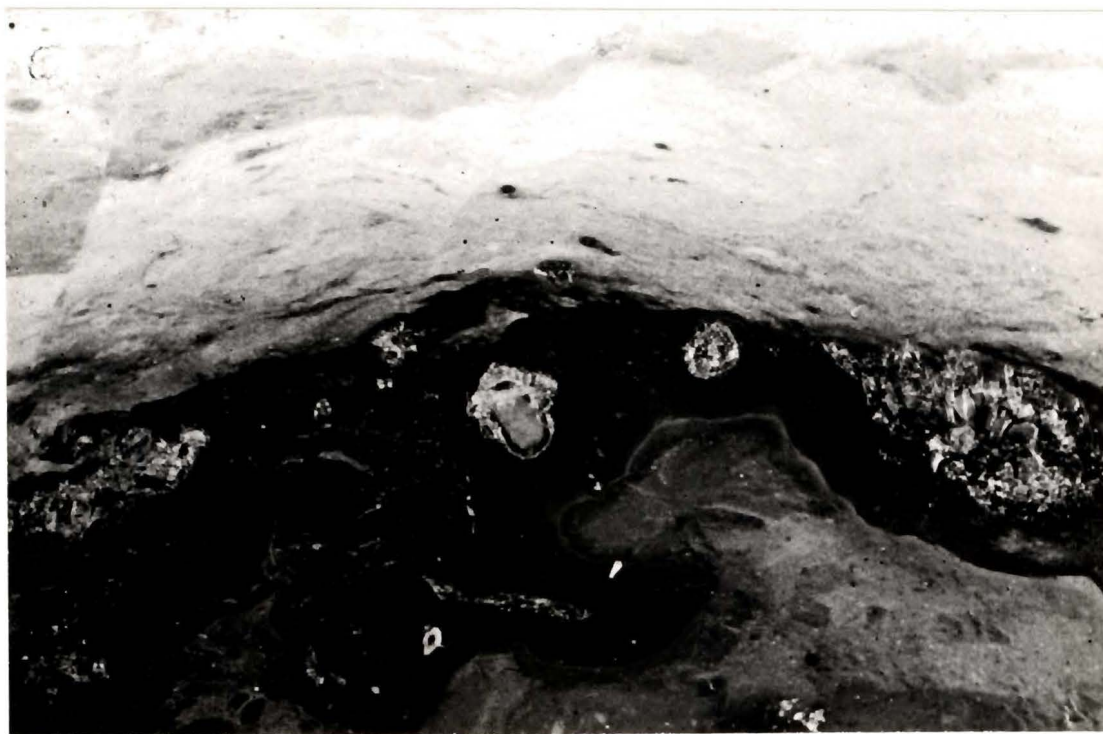


Figure 12b.

Figure 13.--Jarosite body showing two nuclei (arrows) in the Bacon Creek Member at locality 16, sec. 26, T. 13⁴ N., R. 106 W., Slope County, North Dakota.



Figure 13.

consists of unconsolidated silt or sand and gypsum. Concretions of this type are scattered throughout the enclosing sediments although they commonly show a very close proximity to pyrite concretions found in the same sediments.

Thin sections (Figure 14a) show that jarosite is a coating on many of the floating clastic grains and in many cases has partially replaced and highly altered the grains. The limonitic zones are an alteration of the jarosite in many parts of the thin section. In at least one concretion of this type, remnant grains of pyrite partially altered to jarosite, were present in the core of the body.

Pyrite spheres

Pyrite concretions are relatively rare in the Hell Creek Formation and consist of approximately equal parts of pyrite and sand or silt. They are found scattered throughout the sandstone units in the Bacon Creek, Huff, and Pretty Butte Members and although usually found as small (2-5 cm in diameter) isolated spherical bodies (Figure 14b), they may sometimes be present as multiples of such spheres with two or more spheres combined to form a cluster. In the field this concretionary type is found randomly scattered throughout the enclosing sandstone units and usually appears dark gray to black. Pyrite concretions weather to a mass of unconsolidated sand, silt, and gypsum. The pyrite spheres are closely associated stratigraphically with the jarosite concretions and gradational relationships are evident.

Thin sections show only minor shattering of the floating sand grains by growth of the pyrite, indicating very little disturbance of primary structures. A limonitic weathering zone is usually present on the outer surface of the concretion. No apparent organic material is present in the thin section; however, certain areas of pyrite appear to

Figure 14a.--Thin section in plane-polarized light of a jarosite body showing jarosite coating (dark) on sand grains (light) from the Huff Member at locality 1 (90X) (UND Catalog No. 6278).

Figure 14b.--Representative examples of pyrite spheres from the Bacon Creek Member at locality 6 (UND Catalog No. 6295).

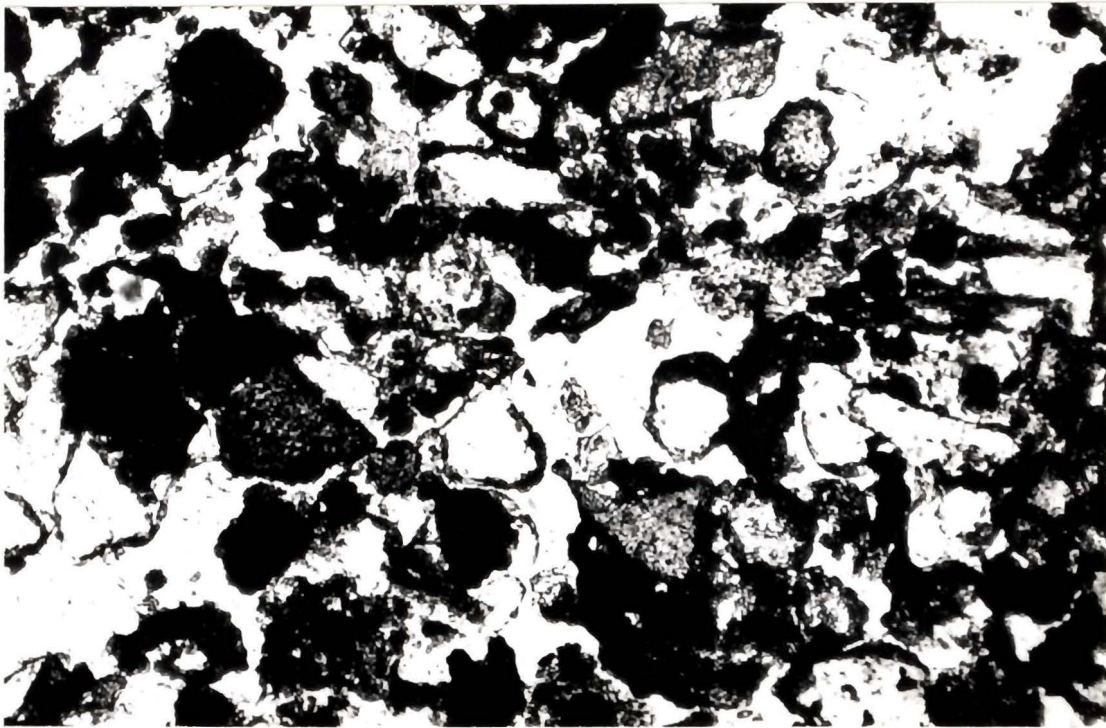


Figure 14a.



Figure 14b.

follow a spherical to nodular form which may be due to totally replaced organic matter of some type (Figure 15a).

Baritic sandstone lenses

Such lenses are rare; only two examples were found, both in a sandy bentonite unit of the Pretty Butte Member. No apparent disturbance of bedding was noted and the two specimens were found along separate bedding planes. However, the extreme rarity of this type of concretion makes a definite statement regarding its relation to the surrounding material nearly impossible. This concretionary type is very striking in the field because of the contrast between the cream-colored concretion and the dark gray color of the surrounding materials. The boundary between the concretion and the surrounding sandy materials is typically gradational.

Thin sections (Figure 15b) indicate a close resemblance of these lenses to the calcareous sandstone lenses and also show what appear to be worm burrows. The clastic grains within the concretion are floating in a matrix of generally massive, cryptocrystalline barite. A few areas of fibrous barite are also present. Replacement as well as fracturing and shattering of clastics is very common throughout the concretion; displacement of the fragments appears to be very minor. A few particles of organic material are scattered throughout the thin section. Small amounts of pyrite with associated limonitic weathering are also present.

Cone-in-cone masses

Calcareous sandstone concretionary bodies having cone-in-cone structures on their upper surfaces are present in various units of the Huff and Bacon Creek Members. This concretionary type is found in sediments which may vary from bentonitic to lignitic sands and silts. The usual shape of this concretionary type is that of a spheroid although

Figure 15a.--Thin section in plane-polarized light of a pyrite sphere showing spherical form (center of photo) of some of the pyritic material from the Huff Member at locality 6 (90X) (UND Catalog No. 6295).

Figure 15b.--Thin section in plane-polarized light of a baritic sandstone lens with characteristics similar to those of calcareous sandstone lenses. Minor pyrite (black) is present in a worm burrow (?) (across center of photo) from the Pretty Butte Member at locality 1 (90X) (UND Catalog No. 6280).

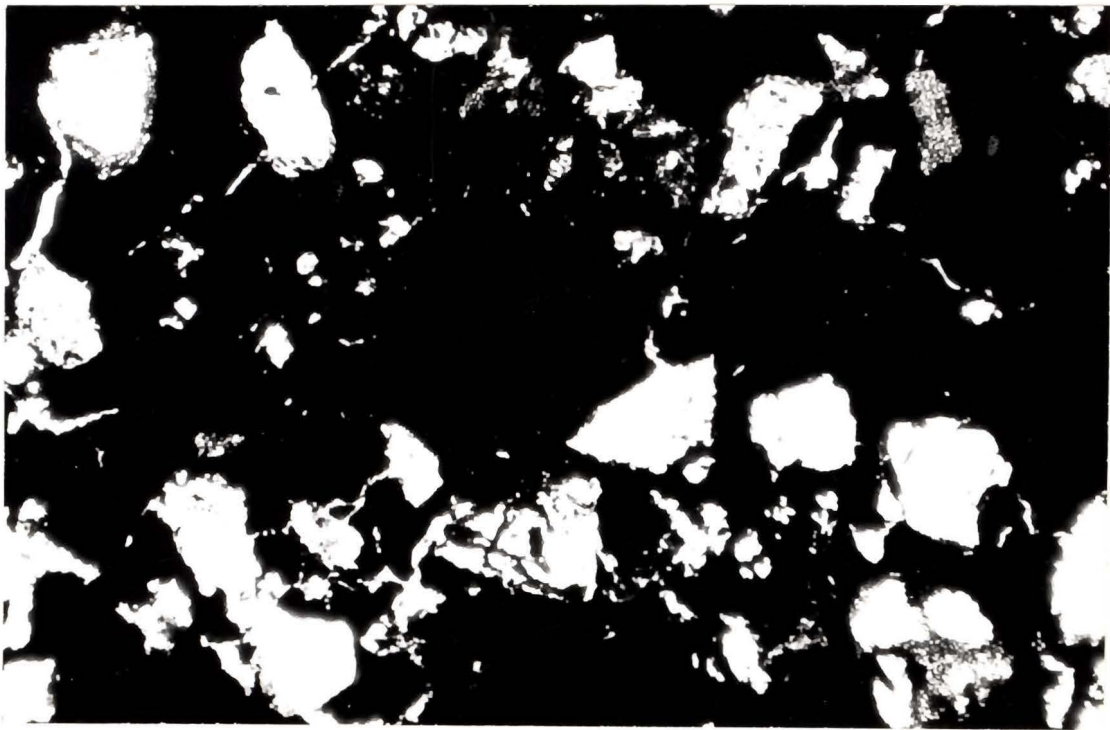


Figure 15a.



Figure 15b.

some specimens may exhibit a highly irregular form (Figure 16a). The longest dimension ranges from 1-3 m.

The concretion invariably consists of a central core of calcite-cemented sand and silt. The upper surface of the concretion is covered with a rind, 5-10 cm thick, of nearly pure, cream-colored calcite displaying typical cone-in-cone structure (Figure 16b). The contact between the two zones of the concretion is typically very sharp as is the contact between the concretion (either cone-in-cone or core) and the enclosing sediments. Bedding in the enclosing sediments, although difficult to distinguish, normally shows differential compaction around the concretion. Remnants of the original bedding are present within the core of the concretion and show only slight indications of distortion.

Thin sections of the core portion of a typical specimen reveal fine, clastic grains floating in massive calcite with scattered patches of iron oxide staining. Lignitic material is quite common. Many of the clastic grains are highly altered and replaced by calcite and numerous examples of fracturing and expansion of the clastic grains are evident. A thin section of the cone-in-cone structure shows nearly pure calcite present along with a few scattered patches of iron oxide staining. Numerous randomly oriented small fractures which are filled with secondary fibrous calcite may be seen transecting the entire area of the thin section.

DESCRIPTION OF NODULES

Siderite masses

Siderite (ironstone) nodules are very abundant in all members of the Hell Creek Formation in southwestern North Dakota. This type of nodule is typically found in lignitic bentonitic sediments as bedded aggregates which follow a distinct bedding plane (Figure 17). Individual

Figure 16a.--Concretion with cone-in-cone layer on the upper surface in the Bacon Creek Member at locality 12, sec. 7, T. 134 N., R. 106 W., Bowman County, North Dakota.

Figure 16b.--Typical specimen of cone-in-cone layer from the Huff Member at locality 6 (UND Catalog No. 6296).



Figure 16a.



CM

1|

2|

3|

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8|

Figure 16b.

Figure 17.--Siderite masses along a bedding plane in the Marmarth Member at locality 5, sec. 26, T. 133 N., R. 106 W., Slope County, North Dakota.

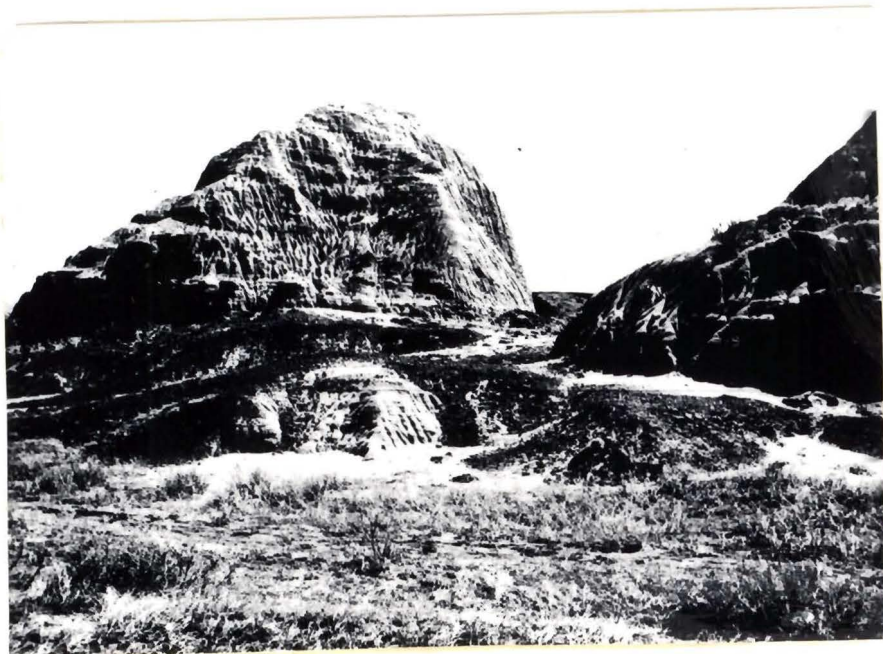


Figure 17.

nodules, however, are not uncommon. In some localities the nodules occur along an interface between two, lithologically different, units; the lower unit always being a very fine-grained clayey sediment. Bedding in the enclosing sediments invariably abuts against the individual nodules which range in size from 0.1-0.2 m in diameter. In many localities calcite veins transect the bedded siderite with individual veins separating adjacent nodules (Figure 18a). The contact between nodule and sediment is invariably very sharp.

The rind is composed of (Laird and Mitchell, 1942, p. 11):

Moisture, water of hydration, and volatile matter . . .	9.04%
Residue insoluble in HCl	10.28%
Ferric oxide Fe_2O_3	47.37%
Manganese dioxide MnO_2	8.01%
Soluble aluminum, calcium sulphate, and undetermined	25.30%

The outer weathered surface of the nodules consists of a thin rind (0.25-0.75 cm thick) of dark brown limonite. This rind is relatively smooth on its outer surface with grains of the enclosing sediments often embedded in it (Figure 18b). The limonitic rind is generally more prominent on isolated nodules than on those which are found as clustered aggregates. Below the limonitic rind, which breaks off along concentric shells bordered by polygonal fractures, is a dark purple to black zone, 0.5-1.0 cm in thickness, which invariably exhibits a pattern of polygonal ridges. The color is probably due to increased manganese dioxide content. The ridges correspond to the polygonal fractures in the overlying rind and commonly each polygon has a raised welt in the middle (Figure 19). This zone in turn is often transected by a second series of polygonal fractures which terminate along a second series of ridges and welts. In at least one specimen a third zone of this type was present. The dark purplish to black zone(s) eventually terminates with a central core of massive tan to gray siderite.

Figure 18a.--Siderite mass which has been transected by a series of calcite-filled fractures from the Bacon Creek Member at locality 12 (UND Catalog No. 6309).

Figure 18b.--Siderite mass showing typical shape and embedded sand grains in the outer rind from the Marmarth Member at locality 5 (UND Catalog No. 6290).

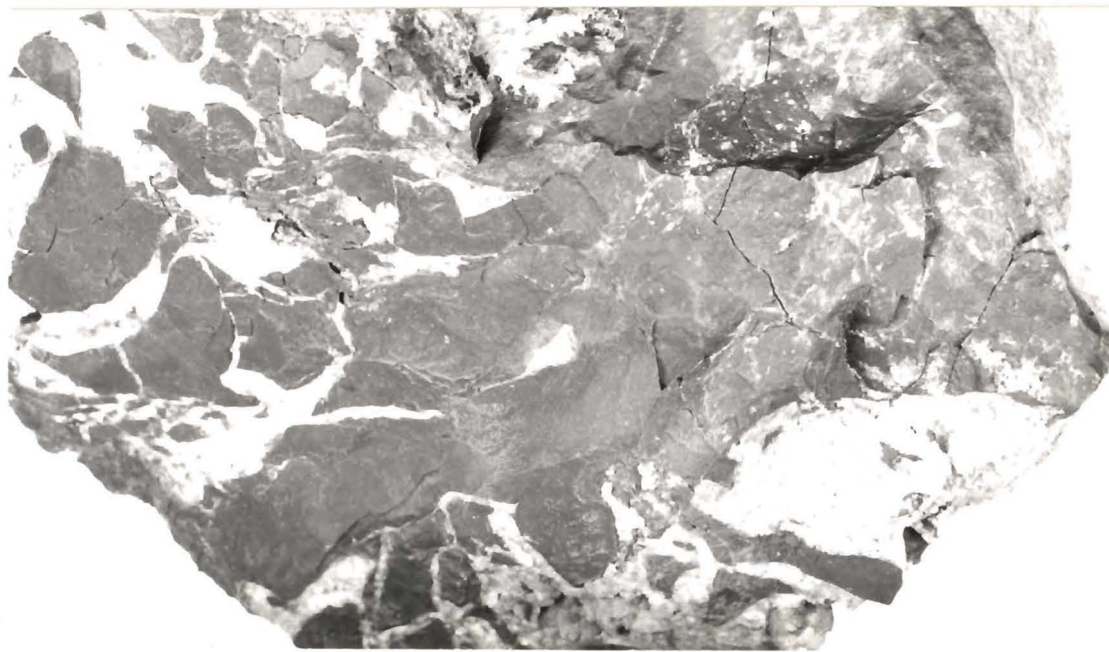


Figure 18a.

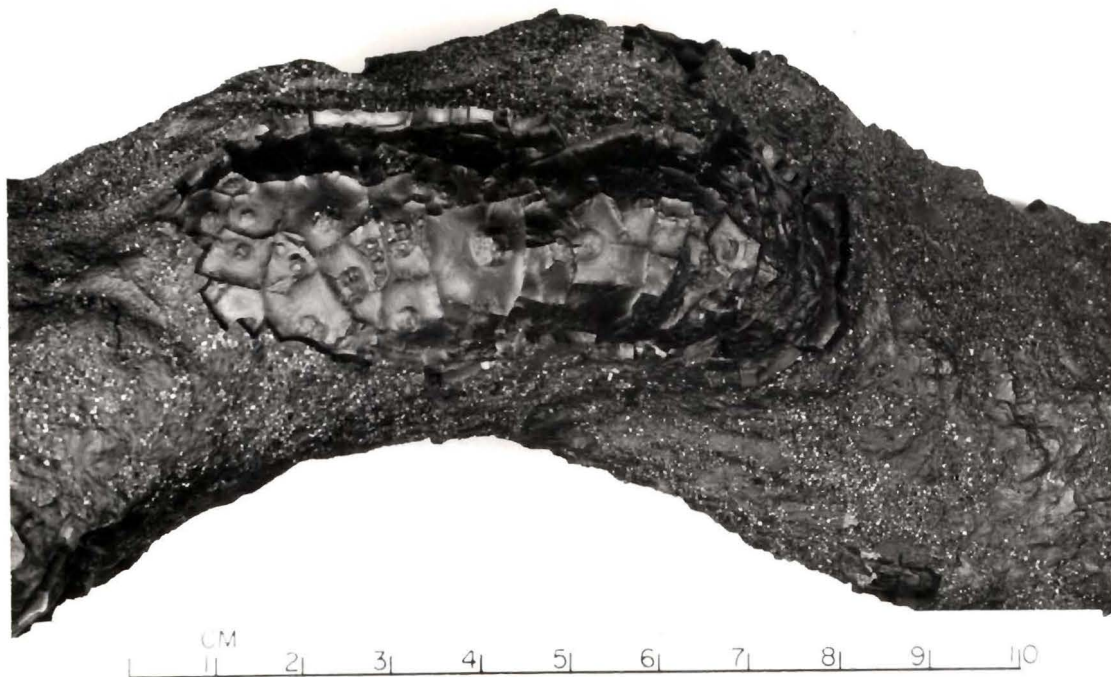


Figure 18b.

Figure 19.---Siderite mass showing sand grains embedded in the
rind and underlying polygonal ridges with associated welts
from the Marmarth Member at locality 5 (UND Catalog No.
6290).



Figure 19.

A thin section of the limonitic outer zone reveals that it is essentially structureless with a few scattered angular clastic grains, mostly quartz and feldspar. The same is true of the siderite core. The contact between the limonitic zone and the core is generally quite sharp; however, gradational features are always present to some degree. In some specimens limonitization follows minor fractures into the siderite core (Figure 20a).

Siderite lenses

True siderite lenses (75 percent or more siderite) are rare in the Hell Creek Formation, but are found in a few of the sandy bentonite beds in the Bacon Creek Member. These lenses are usually concentrated along a certain bedding plane and display minimal disturbance of the included bedding. They range in size from 1-2 m in diameter and 5-10 cm in thickness. Differential compaction of the surrounding sediments is not noticeable. Typical specimens appear as tabular lenses with their long axes parallel to bedding. Individual specimens are amazingly uniform in thickness and are characterized by an outer weathered rind of iron oxides (Figure 20b).

This rind, smooth and without noticeable structure on its outer surface, is of variable thickness depending on the amount of weathering it has undergone.

Thin sections (Figure 21) show the siderite lenses to consist mostly of massive cryptocrystalline siderite in the central areas with included clastic grains following the original bedding of the sediments. The bedding is disturbed, only very slightly, if at all. Texturally the outer rind is identical to the central areas but the siderite has been altered to limonite. Limonitic material follows any fractures or cavities within the concretion. Fracturing of floating clastic grains

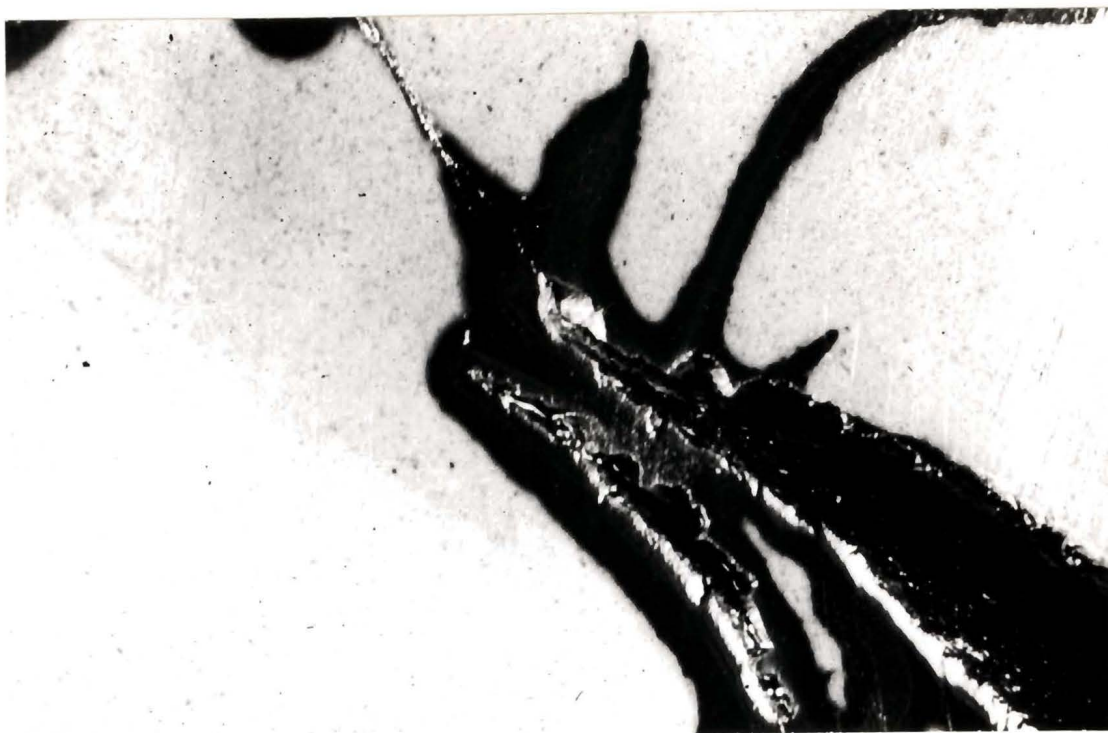


Figure 20a.

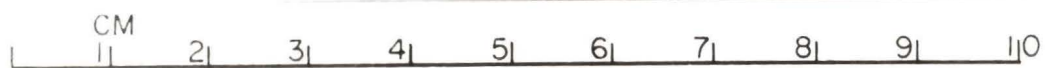
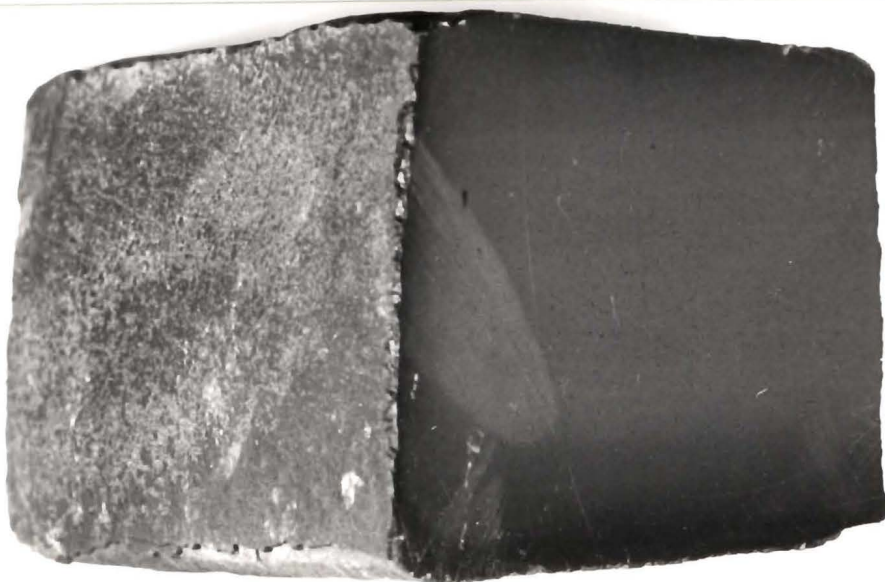


Figure 20b.

Figure 20a.--Sectioned siderite mass showing the contacts between the siderite core and weathered zones, some of which follow fractures from the Huff Member at locality 1 (UND Catalog No. 6301).

Figure 20b.--Siderite lens showing uniformity of vertical thickness and minor limonitization from the Huff Member at locality 6 (UND Catalog No. 6294).

Figure 21.--Thin section in plane-polarized light of a siderite lens showing massive siderite (light), limonitized zone (dark), and uninterrupted bedding from the Huff Member at locality 6 (90X) (UND Catalog No. 6294).



Figure 21.

has not occurred; however, some sideritic replacement of these grains is evident.

Iron oxide spheres

Dark brown to black spheres displaying an extremely irregular "spiny" outer surface are rare in the Hell Creek Formation in southwestern North Dakota. This type of nodule was found only in the bentonitic sand and silt units of the Pretty Butte Member. Nodules of this type are found as individual bodies (0.1-0.5 m in diameter) which follow a specific bedding surface (Figure 22a). The contact between the nodule and the enclosing material always appears very sharp; however, the only examples seen were weathered and therefore may not be representative. The bedding in the enclosing sediments usually appears to abut against the nodules. Displacement of the enclosing sediments by growth of the nodules may have occurred; this is difficult to prove because of the poorly defined bedding in the sediments.

Thin sections (Figure 22b) indicate that nodules of this type consist largely of iron oxide along with minor clay and a few patches of calcite. A few scattered grains of detrital quartz are also present. The iron oxide displays a jagged, spherulitic pattern very reminiscent of the appearance of the outer surface of the nodule. Each nodule apparently consists of aggregates of these spherulitic masses.

CLAY MINERALOGY

Table 1 summarizes the clay mineralogy of various concretions, nodules, and corresponding sediments. X-ray methods as previously described were utilized in these determinations. The identification of both chlorite and kaolinite in most samples is based on the presence of a weak 14.2 \AA reflection and a strong 7.1 \AA reflection. Brindley (1961) stated that this relationship does not always prove the co-existence of

Figure 22a.--Iron oxide spheres in the Pretty Butte Member at locality 9, sec. 16, T. 134 N., R. 106 W., Slope County, North Dakota.

Figure 22b.--Thin section in plane-polarized light of an iron oxide sphere showing distinctive spherulitic structure of the iron oxide from the Pretty Butte Member at locality 9 (90X) (UND Catalog No. 6300).



Figure 22a.

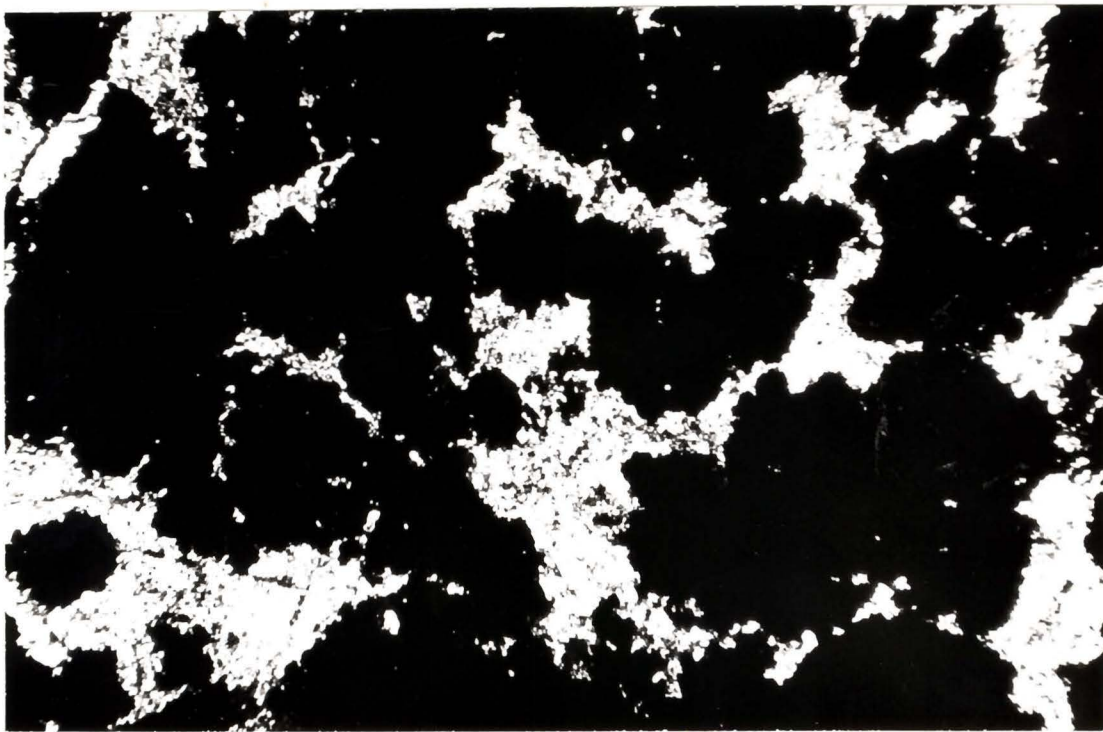


Figure 22b.

the two minerals as the 14.2 \AA reflection of chlorite is sometimes weaker than the 7.1 \AA reflection. However, the consistency of this relationship in the samples analyzed would seem to indicate that both minerals are present.

Additional x-ray work was carried out for the purpose of determining the exact nature of the montmorillonoids present. Oriented smears of several of the highly montmorillonitic materials were made. X-rays of these indicated that calcium and sodium montmorillonite are the only species represented. These are of approximately equal proportions in the materials examined.

Certain trends may be noted regarding the various clay minerals. These include the following:

- (1) Total clay content is always less in the concretion or nodule than in the surrounding sediments implying replacement of the clay in the concretion or nodule by the cementing materials.
- (2) Montmorillonite is invariably absent in concretions and nodules which contain siderite implying growth of the siderite at the expense of the montmorillonite.
- (3) Sediments enclosing sideritic bodies (all types) always contain relatively high amounts of montmorillonite indicating that the availability of iron may have been controlled, at least to some degree, by the alteration of the montmorillonitic materials.

GENETIC MODELS

Introduction

A general overview of the relationships of concretions and nodules to each other and the enclosing sediments is very helpful in considering their origins. The following list consists of those relationships considered to be the most significant (Groenewold and Karner, 1969):

- (1) Great abundance of both concretion and nodules. This common occurrence implies an environment highly suitable for the formation of such structures.

- (2) Orientation parallel to the bedding. Inequidimensional types (Table 1) are oriented with the longest dimensions parallel to the bedding of the enclosing sediments. This suggests an origin related to the physical environment produced by bedded layers.
- (3) Concretions along bedding planes. Many types (Table 1) are concentrated along particular bedding planes supporting (2) above.
- (4) Lack of widespread, laterally continuous concretions or nodules. In no place can a concretion or nodule zone be used as a "marker bed". This implies isolated localities having the proper environment for the formation of these bodies.
- (5) Relation to sedimentary structures. Certain types (Table 1) preserve structures such as cross-bedding and normal bedding while other types disturb or terminate such structures. Such relations indicate time of formation relative to deposition and lithification of the enclosing sediments.
- (6) Location of most types in moderately to highly permeable materials. This indicates the importance of solutions in formation of the bodies.
- (7) Concretions and nodules represent the only well lithified materials in the Hell Creek Formation. This may indicate that many types, particularly calcareous and sideritic concretions represent the initial stages of lithification of some sediments.
- (8) Association with organic matter. Some of the structures may be formed as a result of chemical reactions involving organic compounds.
- (9) Gradational relationships. Many of the types are gradational with respect to one another suggesting a small number of possible origins as opposed to a separate origin for each type.

Calcareous sandstone lenses and "logs"

Due to the nearly identical characteristics of these two concretionary types, they will be treated as one group in this discussion. The only major differences, size and shape, are probably due to factors of relatively minor importance.

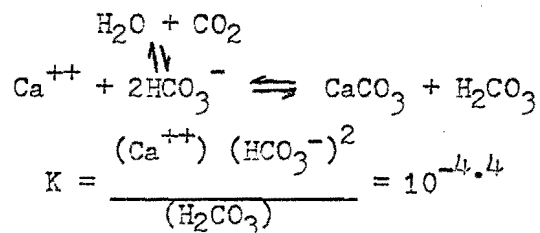
Frye (1967) has given a very good discussion of calcareous sandstone lenses and "logs". He has concluded that expansive growth of calcite

has occurred within the concretion. Perpendicularity of plumose calcite to bedding and the presence of fibrous calcite on only one side of many clastic grains are used as evidence for such growth. However, he considers the very slight reorientation of the fragments of the fractured grains to indicate that the expansive growth has been relatively minor in importance. He considers the relative abundances of clay, chert, and volcanic materials in the enclosing sediments and lack of the same in the concretions along with the high degree of alteration of the few grains of volcanics and chert which are present in the concretions to indicate nearly total replacement of these materials by calcite. Frye believed that this accounts for the apparently undisturbed bedding which is included within the concretions. He also pointed to the lack of compaction of enclosing sediments around the concretions as being indicative of a relatively recent age of formation for the bodies.

The writer is in agreement with Frye's conclusions but would extend them by considering several other characteristics. The fact that the concretions are scattered throughout highly permeable sediments and have their longest axis parallel to the apparent paleodrainage directions is most important. Other interesting features include the presence of limonitized siderite rhombs and the apparent gradational relationships of the calcareous sandstone concretionary bodies with respect to sideritic sandstone lenses. A final consideration involves the gradational aspects of the contacts between concretions and their enclosing sediments.

It is the opinion of the author that the above characteristics point to an environment of formation directly related to groundwater movements. The probable sources for the Ca^{++} ions were the calcium montmorillonites and other silicates (Table 1) present in the sediments and concretionary zones. Frye (1967) stated that the plagioclase grains in the various

sediments are quite calcic. The occurrence of much plagioclase probably indicates that this mineral is a major Ca^{++} source. Therefore it is assumed that these concretions were formed by the precipitation of CaCO_3 , according to the following equation, from the groundwater in zones of relatively high permeability.



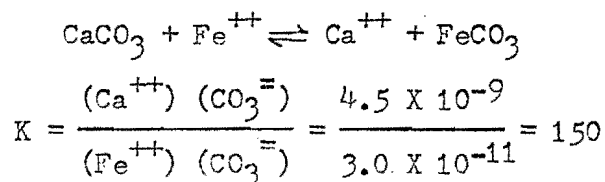
It is difficult to surmise the exact mechanism which has caused this precipitation. Krauskopf (1967) states that plant activity resulting in the removal of CO_2 , or, a rise in temperature might cause the precipitation of CaCO_3 . A rise in pH due to the decay of organic materials within the sediments might also cause the precipitation of CaCO_3 . Plant activity is highly improbable as these concretions were apparently formed while buried. Organic materials are rare and therefore probably were not responsible. Decreased solubility of CaCO_3 would be expected to result from increased temperature at depth. However, an increase in solubility from increased pressure at depth could probably more than compensate for the temperature effect. Krauskopf (1967, p. 67) noted that CaCO_3 is often present in nature in supersaturated solutions for extended periods of time. The great availability of Ca^{++} to the groundwater in these sediments implies that supersaturation could have easily existed. The enclosing sediments are channel sands which very likely contained small fragments of mollusk shells which could have acted as seeds for the precipitation of CaCO_3 . Continued growth resulted in the large lenses and "logs".

A second possible explanation involves temperature changes related

to the frictional drag of the groundwater (Streeter, 1966). In areas where groundwater flow was greatest, the temperature may have been raised enough to cause a shift in equilibrium and the precipitation of CaCO_3 . Once a seed was established in this manner, continued growth of the body could have occurred.

It appears highly probable that the more permeable zones have, in effect, been largely responsible for the initial shapes and sizes of the concretions. It should be noted that the lenses vary from small (longest dimension 1 m) to large features (longest dimension 10 m), whereas the "logs" are consistently large (longest dimension 10-15 m). This relationship seems to indicate that these two concretionary types are gradational; the "logs" represent the more mature features. If this is true then it is possible that as a lens forms the permeability in the unit is decreased by precipitation of CaCO_3 in the pore spaces of the sediment. This in turn will cause the groundwater to flow around the original lens, therefore causing increased vertical growth. Under such conditions it is highly likely that a "log" which is ellipsoidal in cross section will result.

The presence of limonitized siderite rhombs and gradation with respect to sideritic sandstone lenses probably indicates that a delicate equilibrium balance between Fe^{++} and Ca^{++} ions existed during the period of formation. The following equation shows the equilibrium reaction.



Whether calcite or siderite was precipitated was determined largely according to the direction in which the equilibrium balance was shifted (Krauskopf, 1967). In intermediate areas alternate periods of deposition

of both calcite and siderite probably existed. Later oxidation due to near surface exposure and/or lowering of the water table was probably responsible for limonitization of the siderite.

Finally, gradational boundaries between the concretions and enclosing sediments are interpreted to mean that the concretions represent little more than the initial stages of lithification of the sediments. Given sufficient time it seems likely that similar lithification of the remaining portions of the sediments will occur.

Calcareous sandstone irregular masses

The two types of concretions included within this group will be discussed separately. The first type, as previously described, is very similar to calcareous sandstone lenses and "logs", but is more lignitic, shows compaction of surrounding sediments, and is usually restricted to a specific zone.

The compaction points to a relatively early age of formation for the concretions, possibly very shortly after deposition of the enclosing sediments. As discussed by many authors, Weeks (1953), Burt (1932), Rahmani (1970), and Berner (1968), the decomposition of organic matter is often accompanied by a rise in pH and the precipitation of various ions from solution. The organic material present in the concretions has most likely caused such reactions, resulting in the initial precipitation of CaCO_3 in local reducing and high pH environments. The location of the concretions in specific zones is probably due to high organic content and permeability of that zone. After initial precipitation of CaCO_3 , additional CaCO_3 was most likely derived from circulating groundwater and precipitated about the initially formed seed.

Gradational relationships with respect to sideritic concretions of a similar form are probably due to the equilibrium balance between FeCO_3

and CaCO_3 as discussed previously. As in the case of calcareous sandstone lenses and "logs", minor expansive growth within the concretion is indicated by fibrous calcite on one side of the clastic grains and by the fracturing of some clastics without much reorientation of the separated fragments. The relative lack of clays, chert, and volcanics in the concretions is probably the result of calcite replacement, thereby allowing for concretionary growth with minimal disturbance of primary structures.

The one specimen (Figure 5b) which contains branching calcite veins has probably undergone a second period of cementation very late in the history of the concretion. Goldschmidt (1958) noted that groundwater loses CO_2 when in contact with the atmosphere and this in turn results in the precipitation of CaCO_3 . Such a mechanism has probably been responsible for these veins of calcite and has occurred at or very near the surface.

The second concretionary type within this group is rather difficult to explain. Frye (1967, p. 137) gave a brief discussion of the type, stating that they are probably due to "... the growth of calcite in the bentonites to a stage where the grains become interlocking." This seems to be a logical explanation; however, the reason for the precipitation of the CaCO_3 as well as the reason for the concretion's restriction to a specific zone are uncertain. It is probably that the alteration of the various silicate minerals was the source for the Ca^{++} . The CaCO_3 was then deposited with the exclusion of clay along a more permeable zone within the bentonitic unit. Increased temperature due to frictional drag of the groundwater, as discussed previously, may have been responsible for precipitation. At present no other explanation is apparent.

Sideritic sandstone lenses

The gradational relationships between this concretionary type and

the calcareous sandstone lenses is probably indicative of a similar mode of formation for both types. The equilibrium between calcite and siderite is probably an important factor regulating which of the minerals is present. In addition Curtis (1967) stated that siderite apparently forms as a primary precipitate under conditions of relatively restricted groundwater circulation and reducing environments. The most likely sources for the Fe^{++} ions are the various altered silicates in the concretion and enclosing sediments. Lack of differential compaction around lenses again indicates a relatively late age of formation. Later oxidation due to a lowering of the water table and/or near surface exposure are most likely responsible for the limonitization of the siderite.

Sideritic sandstone irregular masses

Identical to calcareous sandstone irregular masses, except for the cementing material, it seems reasonable to assume that the two types formed in nearly identical environments. The only difference would involve a shift of the calcite-siderite equilibrium toward siderite. Wherever reducing conditions were encountered, groundwater relatively rich in Fe^{++} from various altered silicates would precipitate siderite in preference to calcite as the primary cementing material. The gradations between types are therefore the result of fluctuations in the $\text{Fe}^{++}/\text{Ca}^{++}$ ratio. Later oxidation due to a drop of the water table has caused oxidation of the siderite to form limonite.

Lignitic calcareous sandstone lenses

The very obvious slickensided surfaces along with the apparent lack of large scale expansive growth within these concretions implies an early post-depositional origin with concretionary growth occurring before compaction of the surrounding sediments. The high concentration

of organic materials probably raised the pH sufficiently to cause the precipitation of the calcite cement from groundwater. As in previous cases, expansive growth is indicated by clastic grains with fibrous calcite on one side. Fracturing of the clastic grains, without much reorientation, indicates the minor role played by such growth. Again, the clays, chert, and volcanic materials have probably been replaced in the concretion, resulting in only a minor amount of disturbance. The sources of Ca^{++} were most likely the same as those postulated in previous cases.

Lignitic sideritic sandstone lenses

Apparently no gradational relationships exist between this concretionary type and lignitic calcareous types. The sediments in which this type is found are fine-grained and rich in organic materials. The large amounts of included organic debris were probably responsible for highly reducing conditions and therefore for the precipitation of siderite. An early post-depositional origin is therefore implied. The source for the Fe^{++} ions was most likely the highly altered silicates present in the enclosing sediments. The iron, once mobilized, was carried in the groundwater until reducing conditions within the concretionary zone were reached. Oxidation was probably due to later near surface exposure and/or a drop of the water table.

Within this group are concretions which demonstrate a later stage of expansive calcite growth (See pages 28 and 33.). This probably represents a situation where CaCO_3 has precipitated due to a loss of CO_2 from the groundwater at or near the surface.

Bone-cored rounded masses

Concretions of this type are rather perplexing. Upon first examination one might be inclined to postulate that they have resulted from the precipitation of CaCO_3 due to chemical conditions resulting from

the relatively high organic content of the sediments, particularly the bone material. Such a mechanism would indicate an early time of formation under reducing conditions. However, neither of these seem to fit the situation. The fractured and scattered condition of the included bones indicates that the fleshy material had totally disappeared long before concretionary growth was initiated. In addition, the apparent lack of compaction around individual concretions implies a relatively late age of formation. The limonitic staining found in the concretionary zones is also apparently due to primary precipitation from groundwater rather than oxidation of siderite, as no limonitized siderite rhombs are present and is probably a very late, near surface phenomenon.

It therefore appears that the included bones have acted as little more than seeds for the precipitation of CaCO_3 from supersaturated groundwater. The apatite in the bone is probably due to the conversion of the original hydroxylapatite of the bone to fluorapatite by addition of fluorine from groundwater (Krauskopf, 1967).

Coprolite-cored masses

Concretions formed about coprolites are probably of a relatively early post-depositional age. The apatite which comprises most of the concretion is probably the result of phosphate released from the excreta combining with calcium and fluorine in the groundwater (Krauskopf, 1967). Minor faulting in the enclosing rind (Figure 12b) indicates that some expansive growth has taken place after burial. The minor CaCO_3 within the rind (Table 1) is probably a later phenomenon and due to precipitation from supersaturated groundwater around the apatite seed.

Pyrite and jarosite spheres

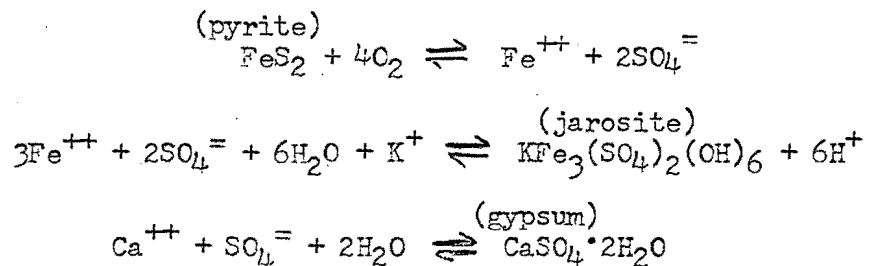
The gradational relationships between these two concretionary types warrants their being considered as one group. Once again several problems are encountered. Pyrite is known to form only in reducing

environments (Curtis and Spears, 1968), (Curtis, 1967), and (Huber, 1958). Such environments result from accumulations of organic matter under oxygen-deficient conditions. However, the sediments in which the pyrite concretions are found are noticeably lacking in organic material of any form. Why then the pyrite? Frye (1967, p. 142) has noted marcasite concretions in the Huff Member in central North Dakota which appear to take their shape from included worm burrows. The spherical shape of the concretions under consideration seems to rule out worm burrows as an organic control. However, under close examination, and a bit of imagination, certain areas of pyrite within the thin section seem to have a semi-spherical to nodular form. It is possible that these areas represent former pellets or similar materials which have caused localized reducing conditions responsible for the formation of the pyrite. As Frye (1967) noted, the negligible disturbance of primary features indicates that pyrite has simply replaced the clay matrix in the sand. The jarosite concretions are clearly secondary, the result of oxidation of the pyrite (Furbish, 1963), (Pough, 1914), and (Warshaw, 1956).

Warshaw (1956) has concluded that jarosite ($\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$) formation in pyritic sediments results from the intermingling of solutions carrying the jarosite components. Oxidation of the pyrite acts as the source of the sulfur and iron. Potassium is derived from other sources. Pough (1914) noted the close relationship between jarosite, limonite, and gypsum around oxidizing pyrite. He concluded that the limonite is the result of further alteration of jarosite and that the gypsum is formed from either excess sulfur released by the pyrite, or after jarosite, as a second alteration product.

It therefore seems reasonable to assume that the jarosite concretions were formed when sulfate and iron-rich solutions migrated outward from oxidizing pyrite spheres and combined with calcium and potassium. The

calcium and potassium were most likely derived from the feldspars in the enclosing sediments. Further alteration of the jarosite has resulted in the limonitic zones. The location of gypsum only within the central core region, and therefore closest to the sulfur source, probably indicates that it has formed as a direct response to excess sulfur in that area. The following equations demonstrate the reactions involved.



Baritic sandstone lenses

The extreme rarity of such concretions indicates that unusual and highly specialized conditions must have been responsible for their formation. The sediments in which the barite lenses are found are fine-grained and contain a fair amount of organic material. It is therefore reasonable to assume that reducing conditions were prevalent early in the history of the sediments and that pyrite was precipitated at this time. The association of pyrite with the burrow (?) in Figure 15b helps to substantiate this assumption. Later oxidation of the pyrite, as indicated by the limonite, could then be responsible for the formation of sulfate which combined with barium to form barite. The major problem with this hypothesis involves a source for the barium. Goldschmidt (1958) indicated that barium is often relatively abundant in potash feldspars, especially sanidine. Assuming that the bentonites in which these concretions are found were formed by alteration of volcanic ash, it therefore seems reasonable to assume that the feldspars were the primary source for the barium. The barium, once mobile, would then have precipitated

as barite in any areas where sulfate ions were encountered--in this case, the immediate vicinity of the oxidizing pyrite. As in the previous cases, the clays have apparently been completely replaced within the concretionary mass; thus a minimum of expansive growth has occurred.

Cone-in-cone masses

The presence of organic materials as well as differential compaction of the enclosing sediments around the concretions implies an early time of formation under locally reducing and high pH conditions. The calcite cement of the core has apparently replaced all the clay within that zone as well as most of the clastic grains. Expansive growth has therefore been relatively minor. Groundwater saturated in CaCO_3 has probably been the principle transporting medium as indicated by the orientation of the longest dimension parallel to bedding. Precipitation occurred wherever highly alkaline conditions were encountered; such conditions being the result of the decay of organic matter. This explanation seems to satisfy the characteristics of the core portion. However, the material displaying cone-in-cone structure requires further consideration. The cone-in-cone layer has been emplaced between the concretionary core and the overlying units and is probably contemporaneous with concretionary growth, or at least, is very early. As Brown (1954) has pointed out, if much overburden had accumulated before crystallization of the cone-in-cone layer, differential compaction rather than separation of the adjacent sedimentary layers would have taken place. A zone of weakness within the bedded units is therefore the most likely explanation for this positioning.

Many hypotheses have been presented regarding the origin of these structures. Tarr (1922) suggested that pressure due to the alteration of aragonite to calcite might be the cause. Later Tarr (Twenhofel, 1932) refuted this theory and proposed that the pressure from overlying beds might be the cause. Dewatering of highly saturated and loosely packed

materials has also been proposed (Shaub, 1937) as well as pressure due to concretionary growth. Gilman and Metzger (1967) have, with a large amount of evidence, gone back essentially to Tarr's original hypothesis of pressure due to alteration of aragonite to calcite.

In considering these hypotheses, some can immediately be eliminated. Dewatering of saturated and poorly packed material seems unlikely. Shaub (1937) shows examples of such structures, all of which are surface phenomenon and therefore do not appear to be pertinent to this discussion. It is equally unlikely that pressure due to concretionary growth has been responsible. As previously stated, expansive growth has been very minor and even if this were sufficient then why should not cone-in-cone structure be found on many more of the concretions in the Hell Creek Formation, especially those which show expansive growth? This leaves pressure due to overburden or pressure due to alteration of aragonite to calcite as the reasonable possibilities. It should be remembered that these are not mutually exclusive.

The writer feels that the discussion as given by Gilman and Metzger (1967) is fairly convincing and that the alteration of aragonite to calcite is therefore the more likely cause. This does not rule out pressure due to overburden; a mechanism which may well have been an accompanying factor. However, until a highly conclusive study of cone-in-cone is completed, a more definite statement regarding the origins of these structures is impossible.

Siderite masses

The manner in which bedding in the enclosing sediments abuts against these essentially structureless masses, as well as the lack of distortion of bedding both above or below the nodules indicates penecontemporaneous precipitation of the siderite probably in the form of a gel as suggested by Frye (1967). The apparent random scattering of included clastics

gives additional evidence for this hypothesis, implying that minor wave action rolled the gel, thus incorporating sand. According to James (1954), a fairly restricted reducing marine environment is the most likely location for such occurrences. The sediments, as previously described, in which these nodules are found are fine-grained, low energy sediments, possibly lagoonal in origin. Thus the proper environmental conditions appear to be fulfilled.

James (1966, p. W40) stated that iron as surface films of oxides on clay may constitute a very large source of iron in many streams. He further stated that " . . . if the clay fraction is accumulated in an environment of low Eh, the oxide may return to solution and be redeposited as glauconite, chamosite, siderite, or sulfide." The abundance of channel and associated near shore sediments in the Hell Creek Formation gives this much credence as the probable Fe^{++} source with precipitation probably occurring when bottom reducing conditions were encountered.

This leaves the polygonal fractures and associated raised welts to be explained. Franks (1969) has given an interesting explanation of similar structures found on sideritic concretionary masses in the Kiowa Formation (Early Cretaceous) of north-central Kansas. It is his opinion that they represent syneresis cracks which have resulted from the dewatering of the colloiddally precipitated siderite. Franks (1969, p. 802) stated that following initial dewatering of the rind and the formation of shrinkage cracks, " . . . colloidal siderite flowed to produce the arcuate raised welts beneath the outer rind. The gentle mounds in the centers of the syneresis polygons presumably remain where flowage of the colloidal siderite did not take place." He has concluded that these structures are restricted only to the outer rind because it is more argillaceous. This explanation seems very logical.

Zonation of these structures in the Hell Creek siderite nodules is then probably the result of a corresponding compositional zonation of the argillaceous materials present. The reason for this is unknown. It may also represent two or more stages of dewatering. Very late, near or at the surface oxidation has been responsible for the limonitized outer rind.

Siderite lenses

The location of these nodules in clayey, probably low energy sediments as well as the very uniform thickness and highly pure nature of the lenses indicates, once again, formation due to the precipitation under reducing conditions of colloidal siderite at or near the sediment-water interface. The only discrepancy involves the apparent lack of compaction of the sediment around these lenses. This would seem to indicate a very late time of formation. However, since the vertical thickness of any given lens does not exceed several centimeters, compaction, if present, could scarcely be distinguishable. The continuation, in an undisturbed manner, of the original bedding through the lenses implies a very quiet water environment. Iron as an oxide film on clays (discussion of siderite masses) was the probable source of the siderite. The lack of polygonal structures on the outer surface is probably the result of a total lack of clays within the lens. Near-surface oxidation is probably responsible for limonitization of the rind.

Iron oxide nodules

The occurrence of these nodules in clayey, generally fine-grained sediments as well as the general structural and textural characteristics indicates a close relationship to sphaerosideritic nodules. Such nodules are commonly found in the underclays of coal seams as well as in other fine-grained sediments.

Hemingway (in Murchison and Westoll, 1968, p. 65) stated that

sphaerosiderite occurs in individual spheruliths " . . . each of which is a radically disposed aggregate of siderite crystals, crystallizing from a single nucleus and forming near-spherical and rough-surfaced body. Sphaerosiderite may occur as individual spheruliths scattered at random through a fine-grained clastic or in nodular or bedded masses in which many aggregates have crystallized together." He further stated that minor amounts of clastic grains are usually included in these nodules. Sphaerosideritic nodules are assumed to be the result of a gel phase early in the history of the enclosing sediments.

From the above discussion it seems reasonable to assume nodules found in the Hell Creek Formation were originally precipitated as a gel in a reducing, possibly lagoonal, environment and that later near-surface oxidation has totally altered them. The textural and structural similarities between these bodies and sphaerosiderite masses as found in many areas of the world are highly indicative of this relationship.

CONCLUSIONS

The following conclusions can be drawn regarding the 14 types of concretions and the 3 types of nodules present in the Hell Creek Formation in southwestern North Dakota:

- (1) The great abundance of concretions and nodules indicates that the deltaic and near shore environments and corresponding sediments of the Hell Creek Formation are ideally suited for the formation of such structures.
- (2) Precipitation as gels or from moving groundwater are the most important mechanisms responsible for the formation of these structures.
- (3) The presence of organic materials and related reducing environments have been important factors in the formation of many of the structures.
- (4) Many types are gradational indicating that minor chemical variations rather than totally different environments have been responsible for their formation.
- (5) The lack of widespread and continuous occurrences of any type of concretion or nodule indicates that they are the result of restricted environments.
- (6) Concretions are post-depositional features whereas nodules are probably penecontemporaneous.
- (7) Because of the lack of lateral continuity concretions and nodules cannot be used as "marker beds" anywhere within the study area.

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